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Bed sediment dynamics in the Gabčíkovo-Topoľníky channel: The three-decade case study

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This paper was focused to find out the impact of silting of Gabčíkovo-Topoľníky channel on the flow conditions at this channel. There were performed the detailed field measurements of bed sediment thicknesses along the Gabčíkovo-Topoľníky since the year 1993 to 2023. Based on the calculation of the values of the average thickness of the bed sediments, there was determined the longitudinal distribution of the bed sediments along the Gabčíkovo-Topoľníky channel, the percentage of silting of the flow area in this channel and the values of the volumes of bed sediments in this channel during the monitored period, which was the main objective and the reasons of this research. This paper relates to evaluation of results from the field measurements at Gabčíkovo-Topoľníky channel during whole monitored period since the year 1993 to 2023, especially compares the results from measurements between the year 1993 and 2023.
Gabčíkovo-Topoľníky channel is one from three main channels of Žitný Ostrov (Rye Island) channel network. The area of Žitný Ostrov (ŽO) is flat land and the velocities in all channels of channel network are very slow. The occurrence of small velocities is considered for main reason of sediment`s aggradation at channel bed. The flow profile of channels is reduced by increased thickness of bed sediments. Consequently, the permanent sedimentation process is unfavourably changing not only the cross-section of channel, but also its longitudinal profile. The channel´s capacity is therefore significantly reduced, e. g. the channel conveys much lower flow as a result of obstruction, lowering the efficiency at channel performance. The volume of sediments is also growing. Bed sediments, their thickness and texture have the important impact to interaction between surface water in channels of ŽO network and groundwater in its surroundings. The results of these measurements are summed up in all tables and figures of this paper and their comparison indicates the growing trend of longitudinal silting of this channel and the volume quantity of bed sediments during the observed period – 30 years.

KEY WORDS: channel network, silting, bed sediments, cross-section and longitudinal profile, volume of sediments

Introduction

Žitný Ostrov – Rye Island is a part of the Danube Lowland which was created by sediments silted from upper part of the Danube River. The area of Žitný Ostrov formed as a flat plain with only small differences in altitude. The channels of Žitný Ostrov (ŽO) are considered the lowland streams where silting of watercourses with sediments significantly affects the flow regime in the stream. The generation of sediments is the result of an accelerated soil erosion or wind erosion in the drainage area most of which is arable land, along with the sediments produced by the construction sites. Additional sources of sediments are the interaction of aquatic vegetation and channel side slopes and bottom, or chemical weathering, such as dissolution. During the winter months the snow and ice melt might be contributors to be accelerated soil erosion followed by the sediment deposition. All channels of ŽO channel network have the low longitudinal slope which is the cause of the occurrence of very low flow velocities in the individual channels of the channel network, as a result of which the particles carried in the flow are deposited to an increased extent, especially at the bottom of the channels. These bed sediments (silt) gradually increase in thickness. Due to the increase in sediment thickness, the flow profile of the channel decreases. The thickness of sediments and their changes have significant impact on the channel flow regime. Due to long-term sedimentation processes, there is an unfavourable change not only in the transverse but also in the longitudinal flow profile, as well as an increase in the volume of bed sediments (Kim et. al., 1999; Zolezzi et. al., 2009; Przybyłek et al., 2017; Monegaglia and Tubino, 2019, Kováčová, 2020; 2022). The bed sediments, their thickness and structure significantly influence the mutual interaction between surface water in the channels of the channel network and the surrounding groundwater in the whole ŽO area (Fendeková et al., 1998; Krčmář, 2003; Dulovičová et al., 2013; Dušek and

Velísková, 2014; Červeňanská et al., 2021).

ŽO is part of the Danube Plain – Fig. 1. ŽO is bordered from the South by the Danube River, from the North by the Small Danube (the Klátovské branch) and from the East by the Váh River (on a short section). Its total area is 1 885 km^2 (Pásztorová et. al., 2013). It is a flat area, with very small height differences: the highest point of the ŽO is located around Šamorín (134 m a.s.l.), the lowest area (105 m a.s.l.) is near Komárno (Gyalokay and Procházka, 1970). Its surface descends in the southwest direction, its longitudinal slope is only around 0.25‰, which was one of the main reasons for building a channel network in this area.

The ŽO channel network was built at the end of the 19th century resulted from the initial need to drain the wetlands on its territory. As a result of the intensification of agricultural production, the need for irrigation on agriculturally cultivated land during the growing season also came into focus. The ŽO channel network was therefore supposed to fulfil a regulatory function as well as a transport function. Later both of these functions were largely affected by the change in the flow profile of the channels, caused by silting with bed sediments, especially by increasing their thickness and also by changes in the permeability of bed sediments in the channel network. The basic elements of the ŽO channel network are channels, pumping stations and sluice gates, primarily used for drainage and associated with them are inflow, filling and water intake objects, necessary for irrigation.

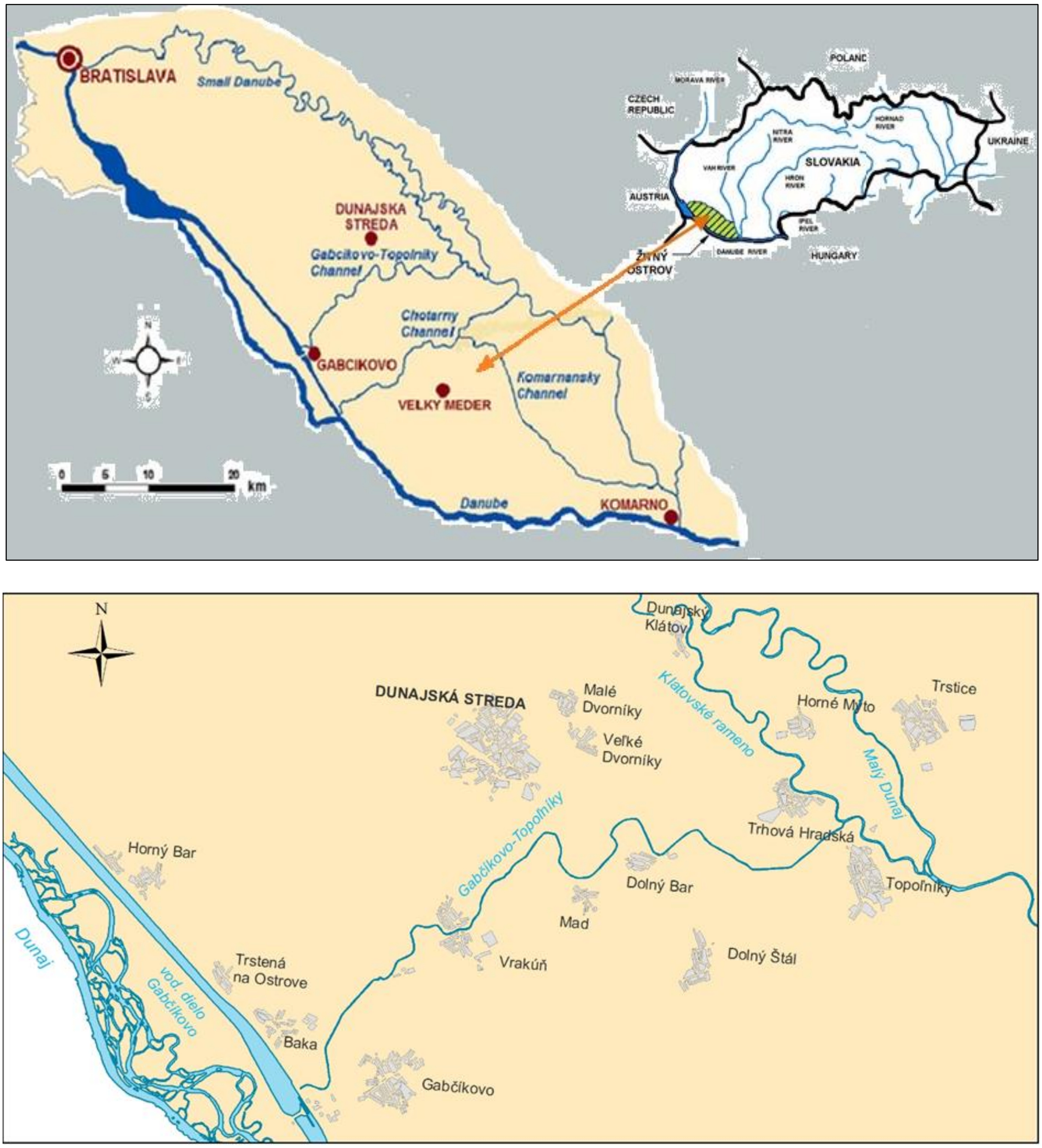

Fig. 1. The area of ŽO (up), more detailed location of G-T channel at ŽO (down).

The G-T channel is about 29 km long, the width of the channel at the surface varies from about 8 m to 17 m. The water depth in the channel (based on measured cross-sections) ranges from 2.0 to 2.60 m. The water drains from this channel gravitationally. All sluice gates, which are intended to drain into the area of Chotárny channel (Aszód), are closed under normal conditions, they are opened only in times of large floods for water capture or in the dry season for the supply of irrigation water. The sluice gates on the side channels of the G-T channel are open during drainage, according to the instructions they are closed for backwater, or to regulate the groundwater level. The G-T channel is connected to the Danube by filling object and flows into the Klátovské branch of the Small Danube between the villages of Topoľníky and Trhová Hradská. The G-T channel is supplied with water from the left side seepage channel of the inflow channel of Gabčíkovo waterworks between the villages of Baka and Gabčíkovo.

Material and methods

As was mentioned above, the silting of the ŽO channel network with bed sediments began to be monitored and recorded since 1993 – on the three main channels of the ŽO channel network (except the G-T channel also on the Chotárny and Komárňanský channel). Field measurements of silting covered approximately 100 km of the channel network, the bed sediment thicknesses were measured in approximately 200 cross-sections. In addition, the samples of bed sediments were also removed in selected cross-sections, in which the great silt thickness were recorded – to determine the saturated hydraulic conductivity of bed sediments, expressing the degree of their permeability (Dulovičová and Velísková, 2005; Dulovičová, 2019; Gomboš et al., 2021).

In 1993, the thickness of bed sediments on the G-T channel was measured using a simple device so called of the necking probe. The measurements were carried out from a portable inflatable boat in cross-sections which were in distance approximately 1.0–2.0 km (depending on the accessibility to the cross-section). At each cross-section the sediment thickness was measured with a regular step of 1.0 m along the channel width. In 2023, over again the control measurements were repeated approximately in the same cross-sections of the G-T channel as in 1993, using the same measurement methodology. From the measured sediment thickness values in each cross-section, the value of the average sediment thickness was determined for each cross-section – as a ratio of the sediment area in the given cross-section and its width (Dobiasová and Dulovičová, 1994). The sediment thicknesses themselves varied significantly along the individual cross-sections, from zero values at the coast line to maximum values that in some places reached a thickness of 1.0 to 2.0 m. However, this large silt did not always occur in the middle of individual cross-sections. It can be explained on the basis of the influence of the changing geometric and hydraulic characteristics of the channel (top width and bottom width of the cross section, side slopes and the longitudinal slope of the channel, hydraulic radius, wetted perimeter).

As already mentioned, in the verticals along each cross-section of the channel at distances of 1.0 m, the measurements of the water depth from the water surface to the top of the sediment and the thickness of the sediment were done. The flow area S_N was computed according to the equation (1), including its silted part (silt area):

$$S_N = \sum_{i=1}^{n-1} S_i = \sum_{i=1}^{n-1} \frac{h_i + h_{i+1}}{2} \Delta X_i \qquad (1)$$

where

S_i – is the partial flow area in the *i*-th measured vertical of the given cross-section [m^2],

h_i – is the sum of the measured water depth to the top of sediment and sediment thickness in the *i*-th measured vertical of the given cross-section [m],

n – is the total number of measured vertical of the given cross-section,

ΔX_i – is the distance between two adjacent measured verticals [m].

Fig. 2 illustrates the variables in equation (1).

The silt area (area of sediment) S_s in the given cross-section was computed according to equation (2), where in that case, d_i was the measured thickness of the sediment in the *i*-th measured vertical.

$$S_s = \sum_{i=1}^{n-1} S_{s_i} = \sum_{i=1}^{n-1} \frac{d_i + d_{i+1}}{2} \Delta X_i \qquad (2)$$

Subsequently, the percentage of silting of the flow area was determined for each measured channel cross-section (Dulovičová and Velísková, 2011). The results of these evaluations for the G-T channel for the monitored period are summarized in Table 1 and Table 2, which are in the section Results and discussion.

According to calculation of the values of the bed sediment average thickness, the longitudinal distribution of the bed sediments in the G-T channel for the monitored period was determined. The graphical representation of these results is at Fig. 3, which is also given in the section Results and discussion.

As a result of permanent sedimentation processes, there was not only an increase in the sediments thickness and thus an unfavorable change not only in the channel cross-sections but also in the longitudinal flow profile of the channel, and also the volumetric amount of bed sediments increased.

From the average thickness of sediments and their distribution along the channel, it was possible to calculate the volume of bed sediments according to the equation:

$$V = \sum_{j=1}^{p-1} \frac{S_{s,j} + S_{s,j+1}}{2} D_j \qquad (3)$$

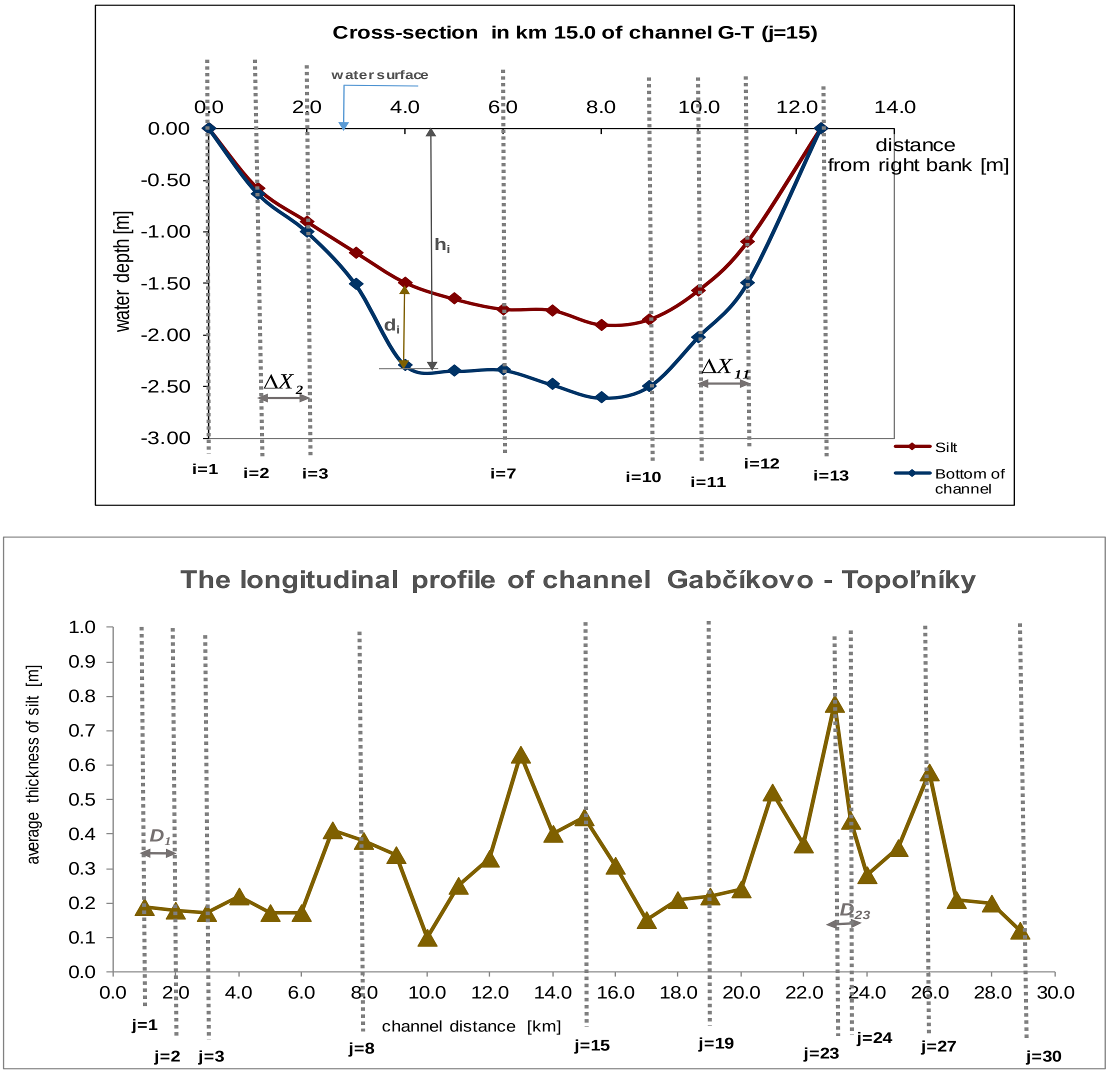

Fig. 2. Scheme showing an example of the cross-section in j=15–15-th vertical in the longitudinal direction of channel (up) and the longitudinal profile of the channel (down).

where

$S_{S,j}$ – is the silt area of individual j-th cross-section,

D_j – is the distance between adjacent j-th and $j+1$-th cross-sections along the channel,

p – is the total number of measured cross-sections along the channel.

The calculated volumes of bed sediments on the G-T channel for the monitored period are summarized in Table 3 – the section Results and discussion. Table 3 includes the values of sediment volumes on the G-T channel for the years 1993 and 2008 (Dulovičová and Velísková, 2007; 2010), supplemented by values obtained from measurements in 2018 and 2023.

Results and discussion

From the evaluation of the measured data on the G-T channel in 1993 and 2023 and their comparison, the real image about the trend of silting of this channel during the thirty-year monitored period was obtained. Table 1 contains the records of sediment thickness in 30 cross-sections, measured along the G-T channel in 1993, together with subsequently calculated values of the average sediment thickness in each cross-section (according to equation (1)) and % of its silting.

Similarly, Table 2 contains the records of measurements on the G-T channel for the year 2023 and the calculation of the values of the average thickness of the sediment in each cross-section, and also the % of its silting in this year.

The values of the average thickness of sediment in the individual cross-sections of the G-T channel from Table 1 and Table 2 were used to the construction of the course of silting up along the G-T channel for the monitored years and their subsequent comparison.

The graphical representation of the longitudinal distribution of bed sediments on the G-T channel is shown in Fig. 3.

When we compare the thickness of deposits on the G-T channel in 1993 and in 2023, we can see at the graph in Fig. 3 that there are alternating sections of increase and decrease in sediment thickness along the entire channel. The chart can be divided into 7 intervals. The first part between km 1.0 and km 4.5 shows an increase in the sediment layer in 2023 compared to 1993, the second part between km 4.5 to km 5.5 shows a decrease in the sediment layer in 2023 compared to 1993, the third part from km 5.5 to km 7.5 shows an increase in sediment thickness in 2023, the fourth part from km 7.5 to km 11.75 shows a decrease in the sediment layer in 2023 compared to 1993, the fifth part from km 12 to km 16.0 shows an increase in the sediment layer in 2023, the sixth part from km 16.0 to km 19.0 shows a decrease in the sediment layer in 2023 compared to 1993 and the seventh part from km 19.0 to km 29.0 shows an increase in the sediment layer in 2023 as compared to 1993. This alternation of decrease and increase of the sediment layer can be explained by the fact that in the sections of the sediment layer decrease the sediments were removed from some selected locations along the channel and transported away to a site in the vicinity of the channel forming a stockpile, that means, a decrease in sediment thickness has occurred as a result of more intensive cleaning of selected sections of the channel as part of maintenance to reduce the thickness of bed sediments. Another reason for increase/decrease of sediments during this long period of time, there was also a gradual displacement of the mass of sediments along the channel. The actual records of the maintenance schedule and the amount of sediments removed were not to our disposition.

In summary, from this graph it is evident that during the monitored period from the year 1993 to 2023, that generally there was an increase in the layer of bed sediments, the longitudinal silting of the G-T channel has been on an increasing trend since 1993. The overall tendency of sediments accumulation is increasing as also evident from Table 3.

As an example of the change in the thickness of bed sediments along the G-T channel from 1993 to 2023, it is possible to present the comparison of silting in 1993 and in 2023 in selected cross-sections of this channel – at the beginning, in the middle and at the end of the channel. Fig. 4a – 4c proves the changes in selected cross-sections of the G-T channel as a result of silting by bed sediments at km 3.0, km 15.0 and km 27.00.

Fig. 5 shows the values of flow cross-section area and silt area in individual cross-sections from Table 1 (calculated on the basis of equation (1)), together with the values of % silting of individual cross-sections for the year 1993. Similarly, the Fig. 6 shows these values for the year 2023 – from the Table 2.

Fig. 7 is the graphical expression of comparison of percentage of silting by bed sediments in the individual cross-sections for the observed period.

Table 1. The average sediment thickness, the flow area, the area of sediment (silt area) and % of cross-section silting along the G-T channel in 1993

Cross-section No.	Stationing [km]	Average thickness of silt [m]	Cross-section area [m^2]	Silt area [m^2]	% of silting
3	3.00	0.14	15.08	1.53	10.2
4	4.00	0.10	14.61	1.24	8.5
5	5.00	0.38	6.91	3.04	44.0
6	6.00	0.06	12.47	0.62	4.9
8	8.00	0.59	31.64	9.97	31.5
10	10.00	0.38	12.83	6.16	48.0
12	12.00	0.30	27.76	5.33	19.2
13	13.00	0.18	21.43	2.52	11.7
14	14.00	0.32	20.03	5.19	25.9
15	15.00	0.12	6.71	1.16	17.3
16	16.00	0.31	18.08	4.64	25.6
17	17.00	0.86	31.27	14.55	46.5
18	18.00	0.40	23.79	5.98	25.1
19	19.00	0.23	21.46	3.88	18.1
20	20.00	0.08	11.51	0.96	8.3
21	21.00	0.16	13.72	1.91	13.9
22	22.00	0.16	13.44	1.93	14.3
25	25.00	0.01	10.88	0.15	1.4
27	27.00	0.09	15.74	1.18	7.5
28	28.00	0.10	15.01	1.40	9.3
29	29.00	0.10	16.64	1.24	7.5
30	29.90	0.04	4.37	0.36	8.1

Table 2. The average sediment thickness, the flow area, the silt area and % of cross-section silting along the G-T channel in 2023

Cross-section No.	Stationing [km]	Average thickness of silt [m]	Cross-section area [m^2]	Silt area [m^2]	% of silting
1	1.00	0.19	30.50	3.27	10.7
2	2.00	0.18	24.85	2.64	10.6
3	3.00	0.17	23.53	2.64	11.2
4	4.00	0.22	28.98	3.69	12.7
5	5.00	0.17	23.88	2.45	10.3
6	6.00	0.17	25.00	2.77	11.1
7	7.00	0.41	35.27	7.64	21.7
8	8.00	0.38	33.81	6.94	20.5
9	9.00	0.34	30.15	5.70	18.9
10	10.00	0.10	22.67	1.60	7.1
11	11.00	0.25	27.74	4.34	15.7
12	12.00	0.33	26.89	5.69	21.2
13	13.00	0.63	30.12	10.12	33.6
14	14.00	0.40	24.58	6.38	26.0
15	15.00	0.45	21.61	5.58	25.8
16	16.00	0.31	21.92	4.88	22.3
17	17.00	0.15	27.08	2.34	8.6
18	18.00	0.21	27.79	3.61	13.0
19	19.00	0.22	27.27	4.02	14.8
20	20.00	0.24	18.84	3.42	18.2
21	21.00	0.52	21.87	8.77	40.1
22	22.00	0.37	21.90	5.93	27.1
23	23.00	0.78	28.64	14.78	51.6
24	23.50	0.44	23.07	8.22	35.6
25	24.00	0.28	13.78	3.12	22.6
26	25.00	0.36	16.25	4.53	27.9
27	26.00	0.58	36.59	11.54	31.5
28	26.85	0.21	20.88	2.88	13.8
29	28.00	0.20	23.54	2.80	11.9
30	28.90	0.12	18.59	1.59	8.6

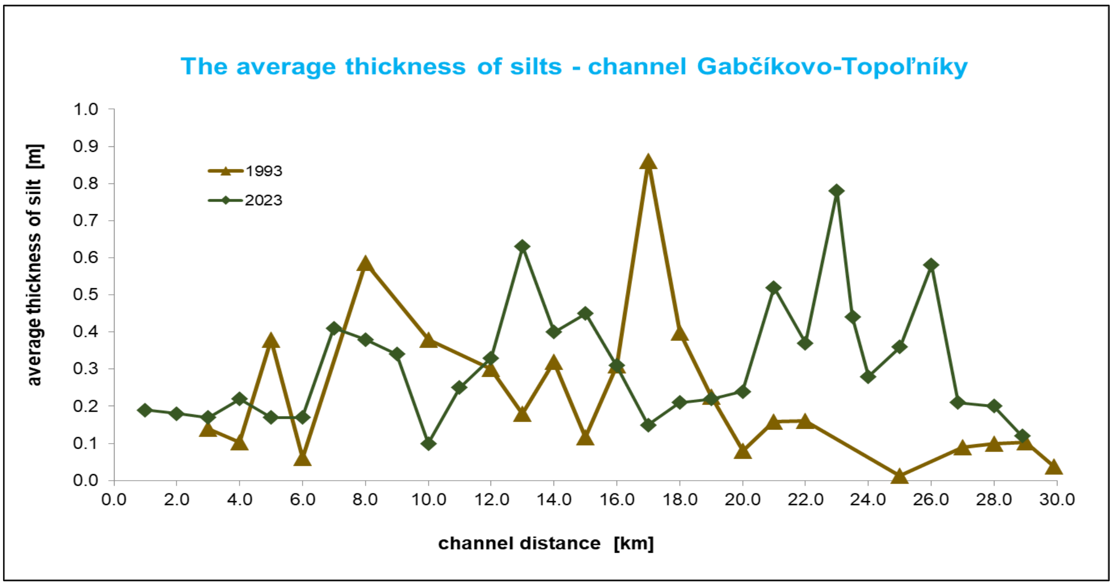

Fig. 3. The comparison of longitudinal silting of G-T channel in 1993 and 2023.

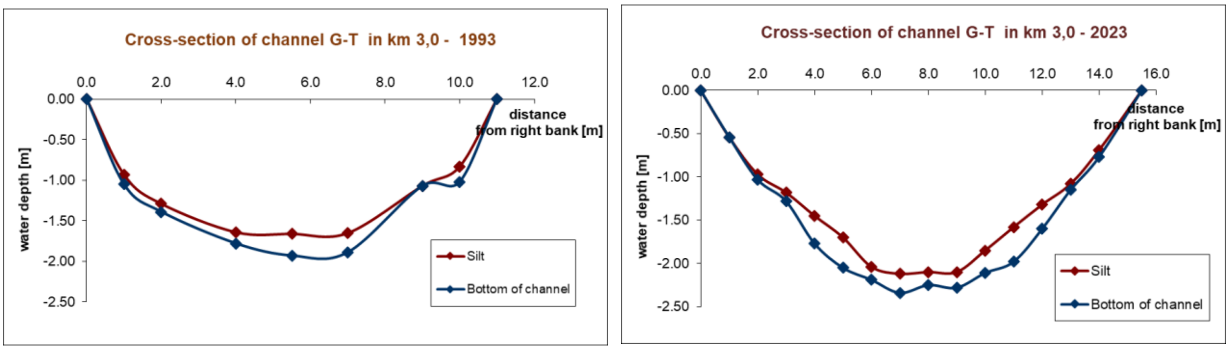

Fig. 4a. Comparison of silting of the cross-section in km 3.00 in the year 1993 and 2023.

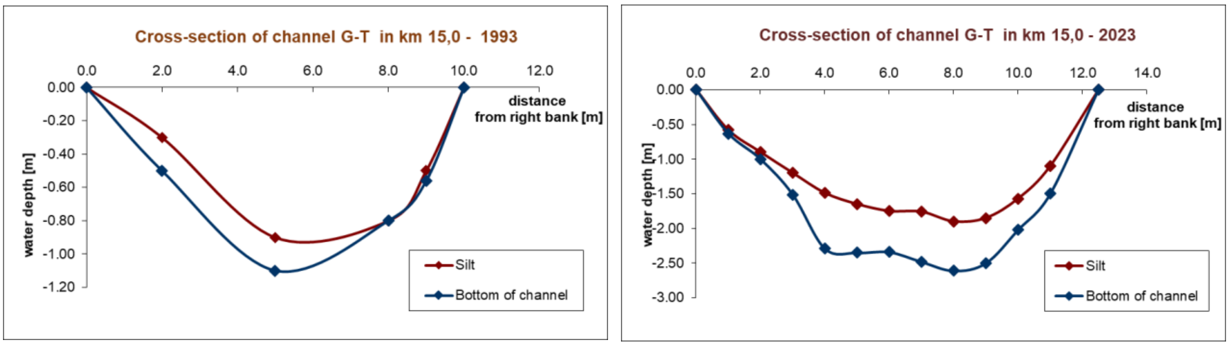

Fig. 4b. Comparison of silting of the cross-section in km 15.00 in the year 1993 and 2023.

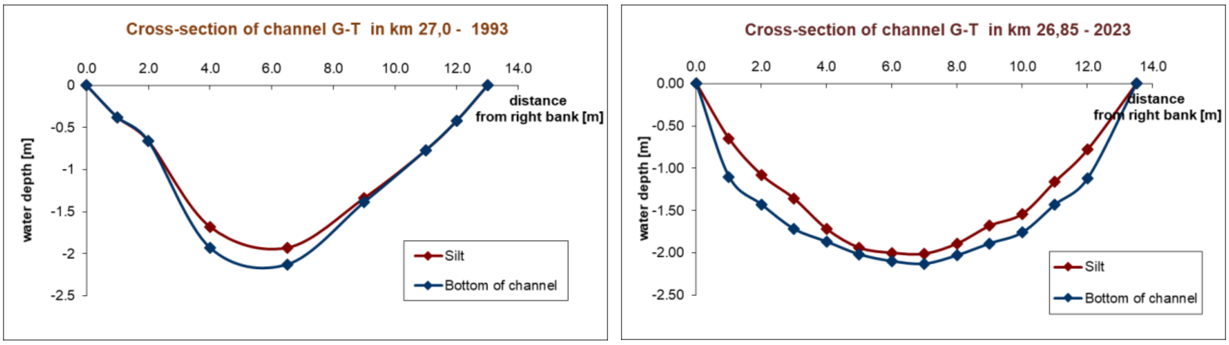

Fig. 4c. Comparison of silting of the cross-section in km 27.00 in the year 1993 and in km 26.85 in 2023.

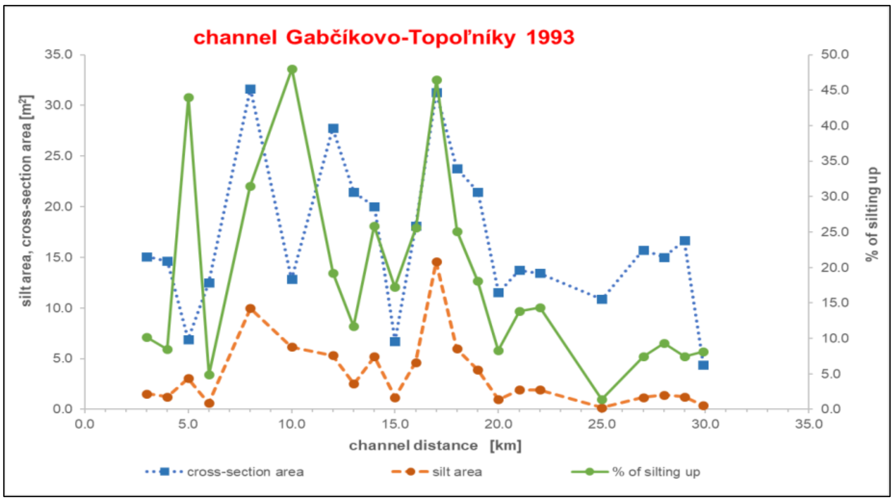

Fig. 5. Percentage expression of cross-sections silting along G-T channel in the year 1993.

In Table 3, the values of sediment volumes are listed, which were calculated based on equation (3). From the data in this table, it is evident that in 1993 compared to 2023, the volume amount of sediments increased. From the comparison of the volumes in 1993 and 2023, an approximately 1.5-fold increase in the volume of sediments was recorded. From the comparison of the volumes in 2008 and 2023, an approximately 1.1-fold increase in the volume of sediments was recorded. From the comparison of the volumes of bed sediments in 2018 and in 2023, its growing trend is also evident – a 1.1-fold increase in the volume of sediments. When comparing sediment volumes between 2008 and 2018, a slight decrease in the amount of sediments was noted, due to more intensive maintenance of channel cleaning during this period. Fig. 8 documents the increase in the amount of bed sediments in G-T channel for the period from 1993 to 2023, respectively its increasing trend.

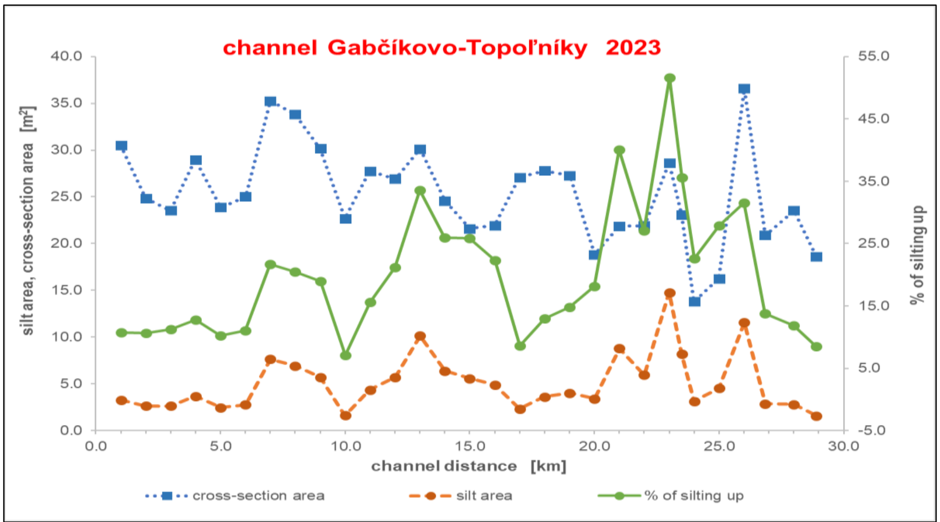

Fig. 6. Percentage expression of cross-sections silting along G-T channel in the year 2023.

Table 3. Total volumes of bed sediments in G-T channel

Year	Total volume of sediments [m^3]
1993	**93 793**
2008	126 411
2018	122 354
2023	**139 150**

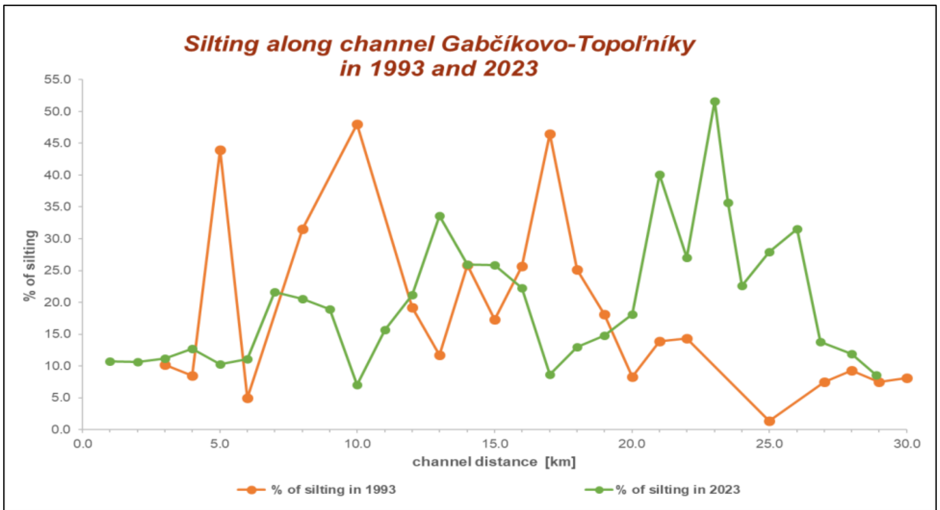

Fig. 7. Percentage expression of silting in individual cross-sections along G-T channel in 1993 and 2023.

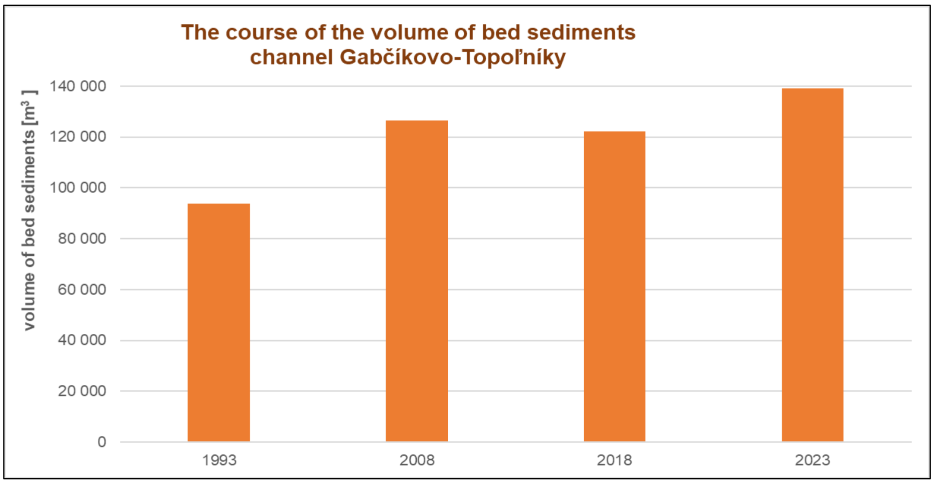

Fig. 8. Representation of the increase in volume of bed sediments on G-T channel for the monitored period from 1993 to 2023.

Conclusion

Based on the evaluation of the field measurements results of G-T channel silting with bed sediments in the years 1993–2023, it can be concluded that during the observed period there was an increase in the layer of bed sediments and thus gradually an increase in their volume. This fact is documented by the graph in Fig. 3, which shows that during the monitored period, the longitudinal silting of the G-T channel gradually increased (except for sections where the flow cross-section of the channel was cleaned as part of maintenance). Comparison of the longitudinal silting of the G-T channel in 1993 and in 2023 in selected cross-sections (at its beginning, in the middle and at the end – km 3.0, km 15.0 and km 26.85, respectively 27.0), shown in Fig. 4a–4c, which document changes in their flow cross-section as a result of silting with bed sediments, also confirms the increase in silting.

From the comparison of the values of the flow area, the sediment area and the percentage expression of silting of individual cross-sections (calculated on the basis of equation (1) and (2) in Table 1 and Table 2), shown in Fig. 7, it is also clear that due to the increase in the thickness of the sediments in 2023, the flow area of individual cross-sections rather decreased compared to 1993, with the exception of the middle section of the G-T channel between km 10.0–12.0 and km 16.0–20.0, where it probably occurred as a result of more intensive cleaning of this section of the channel as part of maintenance to reduce the thickness of bed sediments and subsequently to increase the flow area of these cross-sections, or improvement of the flow conditions on these sections of the G-T channel. This is a confirmation of the assumption that if the administrator of the ŽO channel network strictly follows the operating order and properly performs regular cleaning maintenance of the channels in the whole ŽO channel network, the layer of bed sediments will decrease. This intervention will improve the flow regime in the channel and thereby also improve the mutual interaction between the surface water level in individual channels and the groundwater level in its surroundings within the whole territory of the ŽO. From the comparison of bed sediment volumes along the G-T channel for the observed period, which were calculated on the basis of equation (3) and graphically represented in Fig. 8, you can also see the overall growing trend of the amount volume of bed sediments on the G-T channel for the whole monitored period since 1993.

In conclusion, it can be confirmed that it is necessary to continue the monitoring of the channel network silting on the ŽO, so that our results and recommendations, obtained from field measurements on individual channels, can be used by administrator to improve the flow regime in the whole ŽO channel network, respectively to intensify the mutual interaction of the channel network with the groundwater in the vicinity of the channels and thus to improve its use for the mutual exchange of the water amount between them, according to the current need.

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