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The influence of channel network silting at Žitný Ostrov on the range of interaction between surface and groundwater

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SUMMARY

The movement of water resources, especially the possibilities of their regulation by interaction between surface and groundwaters are the subject matter of attention particularly during the occurrence of extreme hydrologic situation. This work presents the overview of knowledge and results which were achieved at IH SAS in this question. It can show the ways how to optimize the adjudicated processes which emerge during the requirement of emergency intervention. The solution of this task was located at the Žitný Ostrov area because this territory with their existence of channel network is suitable for studying the surface and groundwater interaction. The channel network at Žitný Ostrov was built up for drainage and also to safeguard irrigation water. The water level in the whole channel network system has an effect on groundwater level on the Žitný Ostrov and vice versa. It was been necessary to judge the impact of the channel network silting up by bed silts on the interaction between channel network and groundwater on the Žitný Ostrov. The aim was to evaluate the changes of bed silt state of Žitný Ostrov channel network and consecutively their influence on interaction processes between groundwater and surface water along the channels in the period from 1993 to present. The measurements of bed silt thickness in Žitný ostrov channel network had been started from1993, later they continued at selected profiles of three main channels – channel Gabčíkovo-Topoľníky, Chotárny channel and Komárňanský channel (for checking of the silting up variability). From 2008 the detailed field measurements of cross-section profiles aggradations along these selected three channels have been started. The objective of detailed field measurements was the determination of the silt permeability which is expressed by parameter of saturated hydraulic conductivity. This parameter was determined by two ways – as the saturated hydraulic conductivity obtained from disturbed samples of silt K_p and as the saturated hydraulic conductivity obtained from undisturbed samples of silt K_n. In the first case the granularity of silts was determined as a first step and then was computed their K_p from the empirical formulas according Bayer-Schweiger and Spacek. From undisturbed samples of silts which were extracted along the channels from top, middle and bottom layer of silts, were determined the values K_n by the laboratory falling head method. The valid values K_p on channel Gabčíkovo-Topoľníky ranged from 4,33 10^{-7} to 4,46.10^{-5} m s^{-1}, on Chotárny channel from 5.98 10^{-5} to 2.14 10^{-6} m s^{-1} and on Komárňanský channel fluctuated from 1.93 10^{-6} – 6.09 10^{-5} m s^{-1}. The valid values K_n on on channel Gabčíkovo-Topoľníky ranged from 5.21 10^{-8} – 4.18 10^{-3} m s^{-1} , on Chotárny channel ranged from 8.54 10^{-8} – 2.70 10^{-4} m s^{-1} and on Komárňanský channel fluctuated from 4.72 10^{-7} – 1.26 10^{-5} m s^{-1}. The remarkable results were noticed by comparison of values of saturated hydraulic conductivity from disturbed and undisturbed samples K_p and K_n. On Chotárny channel the values of silt saturated hydraulic conductivity from undisturbed samples K_n approximately hundredfold decreased (from 10^{-6} to 10^{-8} m s^{-1}). On Komárňanský channel the comparison of values K_p and K_n shown that the values K_n from undisturbed samples approximately tenfold descended against K_p.

Simultaneously, the bed silts‘ impact on the groundwater recharge (saturated hydraulic conductivity of silt) was also examined. Determination of the total recharge amount was done by numerical simulation (model SKOKY) and by the so-called method of interaction formulas. These two approaches were applied at the Žitný Ostrov channel network. There were field measurements performed in monitored three main channels and adjacent to obtain correct input data. These characteristics were used for simulation and computation of total recharge along the channels. The total recharge amount was calculated for four alternatives of the surface water levels in the channel and the surroundings groundwater respectively. We chose four simplified variants with the same geological conditions in surroundings area of channels, only water levels of groundwater and in channels were modified. The results of the simulations seem to show greater impact of the silt in the case of outflow from the channels to the surroundings than the inflow into the channel from the surroundings.

Keywords: *bed silts, cross-section profile, surface and groundwater interaction, granularity curve, saturated hydraulic conductivity*

INTRODUCTION

At present in context with climatic change the enlarged demand of sufficient information about mutual interaction between surface and groundwater comes up. The processes related with this question are stick out to importancy especially during hydrological extremes – in drought period, furthermore in flood period and also during accidental ecological disasters with effect of contamination of surface stream or groundwater. Detailed understanding and consequential active regulation of surface and groundwater and their regimes is natural necessity for watermanagement on all the world.

The various aspects of surface and groundwater interaction as e.g. the solution of changes of groundwater resources, the uncertainty of interaction quantification or solution of substances transport by mutual interaction surface and groundwater were researched by several authors (Chen Xi and Chen Xunhong, 2003; Lautz and Siegel, 2006; Baroková and Šoltész, 2011; Rassam et al., 2013; Johnson et al., 2014), also innovational ways of measurement of parameters and interaction rate with various level of exactness occured (Hatch et al., 2006; Kalbus et al., 2006; Weitz and Demlie, 2013).

Questions which are related with problems of surface and groundwater interaction, have been already

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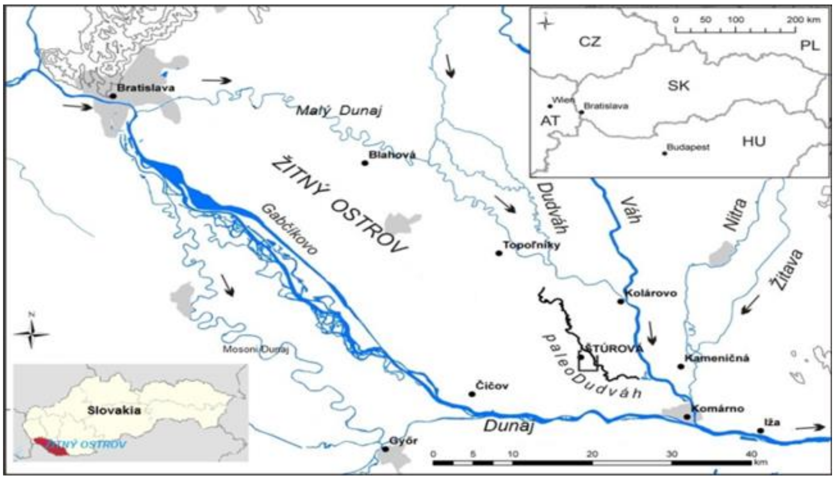
solved on IH SAS in past time (Kosorin, 1997, 2001, 2006; Burger 2005, 2008; Velísková et al., 2010; Dulovičová et al., 2013, etc.). This task was located at Danube Lowland, exactly Žitný Ostrov area, because this territory is very suitable for study of surface and groundwater interaction. It is area of occurrence of the largest resources of drinkable water at Slovakia, but also it is area which is greatly endangered by potential contamination from agriculture production, industry, urban agglomerations, road communications and junkyards of industrial waste. The surface water of Danube River can be also potencial source of region contamination (Čelková, 2013; Kováčová and Velísková, 2012). Thanks to flat texture of this territory and the existence of established channel network Žitný Ostrov became optimal locality for exploration of mutual interaction between surface and groundwaters.

MATERIALS AND METHODS

Žitný Ostrov (ŽO) lies between two branches of the Danube River, on which this river is divided just below the Slovak capital Bratislava: the Danube and the Small Danube – *Figure 1*.

Figure 1: **Site of Žitný Ostrov at Slovakia**



The area of ŽO is approximately 2000 km^2 and represents about 4 % of the Slovak territory. Its average slope is only about 2.5 10^{-4} and this was one of the reasons for building the channel network within this area – *Figure 2* left. The channel network was built up for drainage and also to safeguard irrigation water. The water level in the whole channel network system has effect to groundwater level on the ŽO and in reverse. It was been necessary to judge the impact of channel network silting up by bed silts on the interaction between channel network and groundwater on the ŽO. Aim of this work was to evaluate the changes of bed silt state of ŽO channel network and consecutively their influence on interaction processes between groundwater and surface water along the channels in the period from 1993 to present.

Measurements of channel network aggradation

The measurements of bed silt thickness in ŽO channel network started in 1993 at the channels: Aszód, Gabčíkovo-Topoľníky, Aszód-Čergov, Čergov-Komárno, Čalovo-Holiare and Holiare-Kosihy. Then in 2004 the measurements continued at selected profiles of three main drainage channels – channel Gabčíkovo-Topoľníky, Chotárny channel and Komárňanský channel, for checking of the silting up variability – *Figure 2* right.

From 2008 the detailed field measurements of cross-section profiles aggradations along these three channels have been done to present. The silting up was measured on the presignify determined cross-section profiles of these channels. The transverse distance of aggradation measurement in every profile was 1.0 – 2.0 m. The distance of cross-section profiles along single channels ranged from 2.0 to 5.0 km, with respect to given cross-section profile readability. Each measurement was realized from an inflatable rubber boat by simple measuring equipment (hole probe) – *Figure 3* up and then by echo-sounder Lowrance HDS-10 and EA400/SP – *Figure 3* down.

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Figure 2: **Scheme of channel network at ŽO (left) and situation of three main channels at ŽO – channel Gabčíkovo-Topoľníky, Chotárny channel and Komárňanský channel (right)**

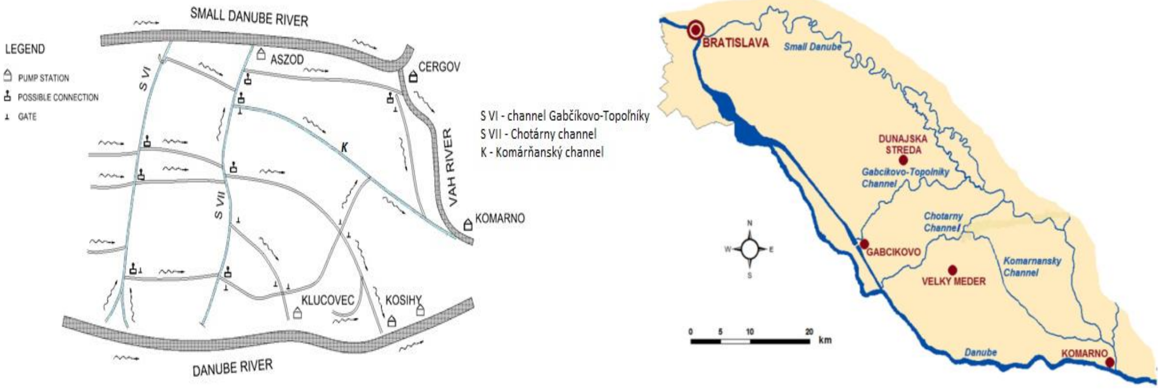
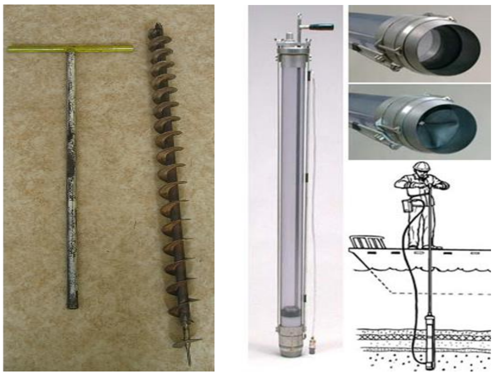


Figure 3: **Aggradation measuring equipments**

Simultaneously the samples of silts were extracted from several cross-section profiles - by auger (in 2004, 2008) and by beeker sampler (from 2014 to present) – see at *Figure 4*. The samples were extracted from top, middle and bottom of silt layer.

Figure 4: **Measuring equipments for silt samples extraction – auger (left) and beeker sampler (right)**



Hydraulic conductivity of silts

The objective of detailed field measurements was the determination of the silt permeability, which is expressed by parameter of saturated hydraulic conductivity (SHC). This parameter was determined by two ways – firstly as SHC from disturbed samples of silt - K_p and secondly as SHC from undisturbed samples - K_n. In the first case initially the granularity of silts was determined and then was computed their K_p according Bayer-Schweiger and Spacek formulas which are quoted in (Mucha, Šestakov, 1987 and Špaček, 1987). These relationships are functions of d_{10} – particle diameter in 10% of soil mass (m) and d_{60} – particle diameter in 60% of soil mass (m). Both of them were determined from granularity curves of the silts. The empirical relationships for determination of SHC by Beyer-Schweiger and by Špaček also depend on different conditions of validity for their application (quoted e.g. in Dulovičová et al., 2016). In the second case the values K_n from undisturbed samples were determined by the laboratory falling head method. The

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detailed description and the methodology of measurement is described in previous works (Šurda et al., 2013; Dulovičová et al., 2016). The equipment with fluctuant hydraulic downslope was used for this measuremnt – *Figure 5*. The formula for calculation of K_n depends on sample height (according scheme on *Figure 5* – *l*) and also on the ratio h_2/h_1 and expired measurement time Δt:

$$K_n = \frac{l}{\Delta t} \ln \frac{h2}{h1} \qquad [\text{cm s}^{-1}] \qquad (1)$$

where K_n is SHC from undisturbed silt samples, l is height of silt sample and Δh is the difference between h_1 and h_2 according scheme on *Figure 5*.

Figure 5: **Simplified equipment for measuring of K_n: 1 – sampling tube, 2 – filter paper and woven wired sieve, 3 – Petri dish, 4 – extension piece, 5 – confining ring**

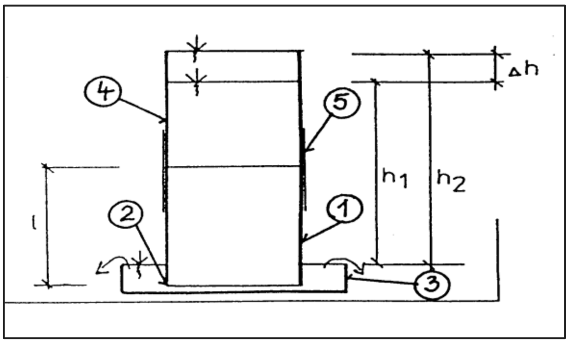

Figure 6 shows the example of silt sample extraction from inflatable rubber boat by beeker (left) and saturation of undisturbed silt samples in Kopecky rollers during laboratory falling head method (right).

Figure 6: **Extraction of silt sample from channel by beeker (left), saturation of undisturbed samples during laboratory falling head method (right)**

Impact of silting up to range of interaction between surface and groundwater

The interaction of surface-water bodies with groundwater systems is governed by the positions of the water bodies relative to the ground-water flow system, the characteristics of surface-water beds and underlying geological materials, it depends on relation between the groundwater head at the stream interface and the stream stage. A stream may gain water from the seepage of groundwater through the stream bed (gaining stream; stream stage < groundwater head) or lose water to groundwater by outflow through the stream bed (losing stream; stream stage > groundwater head). The exchange of water quantity between open channel and groundwater reservoir is realized through their contact areas. The seepage from the groundwater into the stream (or conversely) is a key hydraulic characteristic, which is given as an inflow/outflow in $m^3 s^{-1}$ over the channel bottom area, allocated on one meter of channel length. This lateral flow q_{bm} in $m^2 s^{-1}$ is expressed by continuity equation:

$$q_{bm} = \frac{\partial S}{\partial t} + \frac{\partial Q}{\partial x} \qquad (2)$$

where left element of this equation means partial variation of discharge cross-section S in partial time t and right element represents the partial change of discharge Q along partial channel section X. The intensity of this characteristic determines the stream impact onto the surrounding groundwater and conversely. The discharge q_{bm} constitutes the input characteristic in case of surface water or the boundary condition in case of groundwater. In our case was used the three dimensional hydrodynamic model SKOKY for simulation of groundwater and surface water flow in their mutual interaction which was developed at the IH SAS Bratislava by Dr. Kosorin (Kosorin, 2001). Model SKOKY is based on a mathematical model, consisting from equations:

$$\text{grad } P + v/k = 0 \qquad (3)$$

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where P is pressure function (potencial $P = y + p/g\rho + const$), v is a velocity vector, p is the hydrodynamic pressure, y is the vertical coordinate and k is hydraulic conductivity coefficient.

and $$\mathrm{div}\, v = 0 \quad (4)$$

Model is completed ordinarily with correctly stated boundary conditions (the actual measured values from existing databases of observation were used).

Also there was used the so-called method of interaction formulas for determination of water recharge. Kosorin, 2001 derived a general relation for the inflow (from groundwater into surface water) or outflow (from surface water into groundwater):

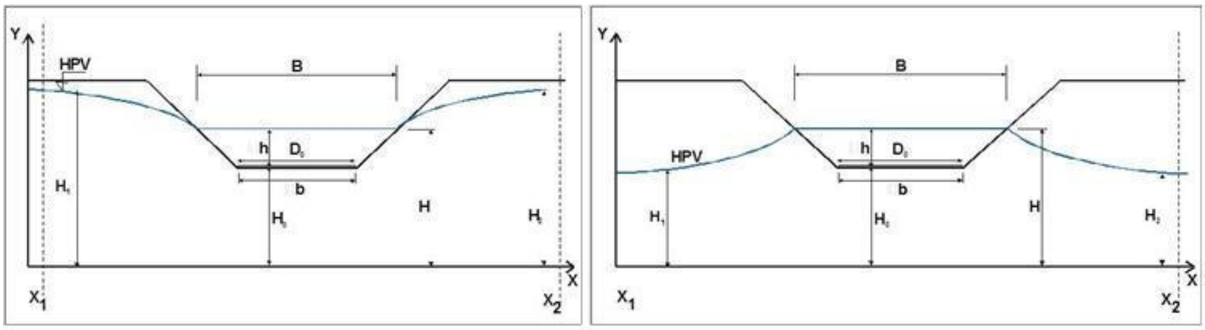
$$q_{bm} = a_1\varphi_1 + a_2\varphi_2 + a_3\varphi_3 + \ldots. + a_i\varphi_i \quad (5)$$

where $\varphi_1, \varphi_2, \ldots., \varphi_i$ are the interaction formulas and $a_1, a_2, \ldots, a_i$ are their parameters which we had to find. The interaction formulas include the influence of variable parameters for the evaluation of the inflow/outflow, they depend on the water level in the stream and equally on the groundwater level in the adjacent area. This relationship is expressed as:

$$\varphi_i = f\,(h, H_0, H_1, H_2) \quad (6)$$

where H_1 is groundwater level in input cross-section X_1, H_2 is groundwater level in output cross-section X_2. The course of groundwater flow is in direction axix X, from X_1 to X_2. Cross sections X_1 and X_2 are at symmetrical distances from the cross section centre line and H is the sum of the groundwater body thickness from impermeable bedrock to a channel bottom and depth of water in the stream, refer to *Figure 7.*

Figure 7: **Schema of mutual interaction between the surface flow and the groundwater for a symmetrical stream cross section - gaining stream (left) and losing stream (right)**



This figure presents the schema of mutual interaction between the surface flow and the groundwater for a symmetrical stream cross section with water depth h in case of gaining stream. Scheme for losing stream is the same, only with one changed detail: $(H_1 = H_2) < (H = H_0 + h)$. The silt thickness D_0 is symmetrical across whole bottom width. HPV is the groundwater level. The impact of geological characteristics of the surroundings at cross section and its geometrical parameters is expressed as:

$$a_i = f_i\,(H_0, b, k_{fGW}, k_{fS}) \quad (7)$$

where $i = 1,2,3,\ldots.$, k_{fGW} is saturated hydraulic conductivity of the groundwater body, k_{fS} is saturated hydraulic conductivity of the bed silts of a single cross section and b is the channel width in the bottom of this cross-section.

Four variants were simulated and compared. Variant I. was a symmetrical double-sided groundwater inflow into a symmetrical stream cross-section with the water depth h. The value of the total recharge was: $q_{I.} = + q_1 + q_2$ ($m^2\ s^{-1}$), where q is total outflow/inflow from/into a stream, q_1 is discharge through input cross section X_1 and q_2 is discharge through output cross section X_2. Variant II. was a symmetrical double-sided outflow from a symmetrical stream cross-section (with water depth h) to the groundwater, the total recharge was: $q_{II.} = - q_1 - q_2$ ($m^2\ s^{-1}$). All variants used the groundwater level in the input cross-section X_1 identical with the groundwater level in the output cross section X_2, that means $H_1 = H_2$ and at the same time the water depth in stream is h. Variant III. was a double-sided groundwater inflow into a symmetrical stream cross-section with the same groundwater levels $H_1 = H_2$ and with water depth in the stream h/2. The relation for the groundwater recharge for this variant is the same as for variant I., only water level in the cross section is h/2. Variant IV. was a symmetrical double-sided outflow from a symmetrical stream cross-section with water depth 2h and with the same groundwater levels $H_1 = H_2$. The recharge for this variant is the same as in variant II., only the water level in the cross section is 2h.

RESULTS AND DISCUSSION

According to results of measurements at these three selected channels during the monitored period 1993 to 2018 it could be demonstrated that on channel Gabčíkovo-Topoľníky was the big fluctuation in silting up, but at the same time significantly larger aggradation

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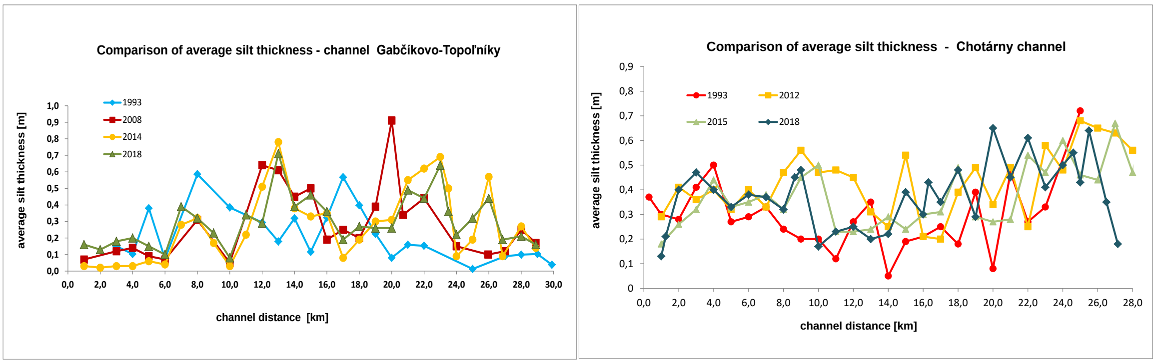
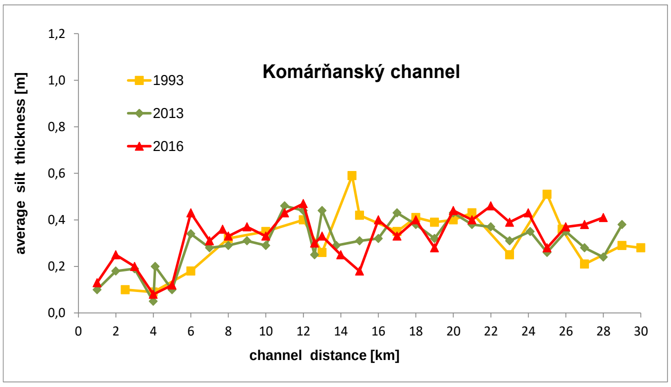
in its middle part and in its lower part (outfall to Danube river) is evident. On Chotárny channel was observed also variation in aggradation of channel and about from its middle part was found slightly increased trend of silting up with growing stream log. The results of silting up measurements at these two selected channels are demonstrated on *Figure 9*.

Figure 9: **Example of average silt thickness comparison during monitored period - at channel Gabčíkovo-Topoľníky (left) and Chotárny channel (right)**



On Komárňanský channel also was observed fluctuation in aggradation of channel and also is evident softly increased trend of silting up with growing stream log from middle part of this channel which was repeated during whole monitored period 1993 to 2016, but on this channel were not so large aggradation deflections as for before mentioned channels. The presumed linear increasing of silting up did not confirmed. In generally the channel network aggradation gradually enlarged (excepting local parts in which the purification was carried on) and the silt thicknesses increased – *Figure 10.*

Figure 10: **Course of average silt thickness during monitored period at Komárňanský channel**



The results of assessment of SHC of silts from disturbed samples K_p which were calculated according to Bayer-Schweiger and Spacek formulas, are following. The valid values K_p on Gabčíkovo-Topoľníky channel ranged from 6.99 10^{-9} to 1.08 10^{-4} m s^{-1}, on Chotárny channel from 5.98 10^{-5} to 2.14 10^{-6} m s^{-1} and on Komárňanský channel fluctuated from 1.92 10^{-6} – 6.09 10^{-5} m s^{-1} (Dulovičová et al., 2016; Dulovičová et al., 2018).

The results of assessment of SHC of silts from undisturbed samples K_n which were found out by falling head method and calculated according to the *Eq. 1*, are following. The values K_n on Gabčíkovo-Topoľníky channel ranged from 5.21 10^{-8} to 4.18 10^{-3} m s^{-1}, on Chotárny channel ranged from 8.54 10^{-8} – 2.7 10^{-4} m s^{-1} and on Komárňanský channel these values fluctuated from 4.72 10^{-7} – 1.26 10^{-5} m s^{-1} (Dulovičová et al., 2016; Dulovičová et al., 2018).

We made also the comparison of SHC values from disturbed and undisturbed samples of silts. On Chotárny channel there were detected hundredfold lower values for undisturbed samples (K_n) opposite values of disturbed samples (K_p). By comparison of top and bottom layer of silts was detected that top layer of silt had ten times higher values of K_n opposite to K_p, the bottom layer had twenty times higher values of K_n opposite K_p. On Komárňanský channel was the value of K_n ten times lower opposite K_p, there was detected also the decrease of values K_n opposite K_p in both layers - in top and bottom layer, too. The illustration of comparison of valid values K_p and K_n on Komárňanský channel is represented at *Figure 11*.

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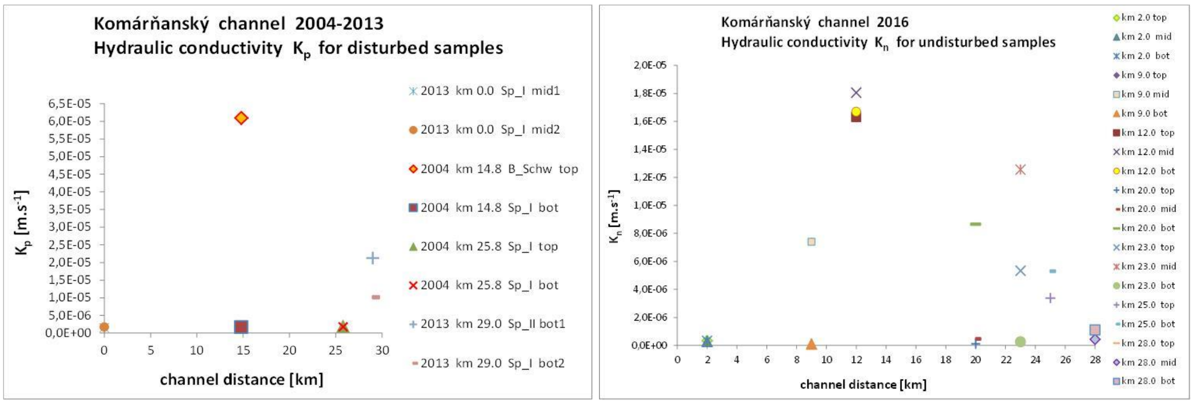
Figure 11: **Example of graphic representation of comparison of values silt hydraulic conductivity from disturbed and udisturbed samples on Komárňanský channel**



Lastly the impact of bed silts in channel on surroundings groundwater aquifer through their mutual interaction and recharge amount was evaluated. Two ways for computation of water amount were applied: model SKOKY and method of interaction functions. We calculated recharge for 4 hydrological variants, in which we used gained results from field measurements described above. At first we calculated it with model SKOKY and then we had to calculate unknown interaction formulas parameters $a_1 – a_4$ for each cross-section profiles. The calculation of parameters a_i was made by matrix method solution of linear equations system. When the difference between $q=(SKOKY)$ and $q= f(\varphi_i)$, which was calculated by interaction formulas, was negligible (less then 10%), we considered selected number of interaction formulas as sufficient. When the difference was not negligible (differences were higher then 20 %), we could not consider the calculation as sufficient, that means we recommended increase the number of interaction formulas and to input another dependencies. Because our intention was judgement of sediment influence on recharge, so we did not solve number of interaction formulas and accuracy of this approach. The recharge calculated through interaction formulas, of which differences were higher then 20%, we did not accept for judgement. The example of total recharge quantities in Chotárny channel from all 4 variants is in *Table 1*.

Table 1

Verification of interaction formulas parameters validity for total recharge quantities in Chotárny channel (Dulovičová et al., 2013)

I. variant $H_1=H_2=H_0+2h$ (Δ= h)					
Profile	1	3	7	10	15
$q_{I.}$ (φ) [$m^2 s^{-1}$]	0.002976	0.003031	0.001382	0.000964	0.001736
$q_{I.}$ SKOKY [$m^2 s^{-1}$]	0.003274	0.008219	0.002070	0.004495	0.001777
Difference	0.000298	0.005189	0.000688	0.003531	$4.121\ 10^{-5}$
%	10.01	171.17	49.78	366.29	2.36
II. variant $H_1=H_2=H_0$ (Δ= -h)					
Profile	1	3	7	10	15
$q_{II.}$ (φ) [$m^2 s^{-1}$]	-0.001325	-0.001117	-0.000515	-0.000646	-0.000194
$q_{II.}$ SKOKY [$m^2 s^{-1}$]	-0.000886	-0.000691	-0.000284	-0.000392	-0.000261
Difference	0.000438	0.000426	0.00023	0.000254	$6.685\ 10^{-5}$
%	-33.13	-38.14	-44.85	-39.32	34.54
III. variant $H_1=H_2=H_0+h$ (Δ= h/2)					
Profile	1	3	7	10	15
$q_{III.}$ (φ) [$m^2 s^{-1}$]	0.001663	0.008643	0.001528	0.002333	0.000465
$q_{III.}$ SKOKY [$m^2 s^{-1}$]	0.002442	0.006161	0.002172	0.003264	0.001902
Difference	0.000779	0.002482	0.000644	0.000931	0.001437
%	46.84	-28.72	42.15	39.91	309.03
IV. variant $H_1=H_2=H_0$ (Δ= -2h)					
Profile	1	3	7	10	15
$q_{IV.}$ (φ) [$m^2 s^{-1}$]	-0.001997	-0.001536	-0.001926	-0.001943	-0.000366
$q_{IV.}$ SKOKY [$m^2 s^{-1}$]	-0.000815	-0.001616	-0.000687	-0.001134	-0.000366
Difference	0.001182	8.0558E-05	0.001239	0.000810	$4.788\ 10^{-5}$
%	-59.19	5.21	-64.33	-41.64	0.00

The values of total recharges from all four variants are in this table. Profiles, in which it was calculated, were distributed along the whole Chotárny channel.

CONCLUSIONS

The aim of this paper was to analyse and evaluate the impact of bed sediments quantity and its distribution along drainage channel on mutual interaction of water level in channel and in surrounding groundwater. Locality, at which this problem was solved, was the area of channel network and its surroundings at ŽO. The silt thicknesses from 1993 to 2018 has been changed as show *Figure 9* and *Figure 10.* According to results of measurements it could be demonstrated that on all three channels during the monitored period was the big fluctuation in silting up, but at the same time significantly larger aggradation in their middle and lower part is evident. The presumed linear increasing of silting up did not confirmed. Generally we can remark that channel network aggradation gradually enlarges (excepting local parts in which the purification was carried on) and the silt thicknesses increased. Also the volume of silts extended. Our research is useful for channels' maintenance program purposes. The approximate estimates of the sediment depositions will facilitate to predict future silting up in the channels and serve as a planning tool.

Determination of the total recharge amount was done by a numerical simulation (model SKOKY) and by the so-called method of interaction formulas, both approaches were applied at ŽO channel network. The field measurements were performed in monitored three main channels and adjacent to obtain correct input data. The characteristics of SHC - K_p and K_n were used for simulation and computation of total recharge along these channels. The total recharge amount was calculated for 4 alternatives of the surface water levels in the channel and the surroundings groundwater respectively. We chose four simplified variants with the same geological conditions in surroundings area of channels, only water level of groundwater and in channels were modified as shows *Figure 11*. The results of the simulations and computation of total recharge along these channels seem to show greater impact of the silts in the case of outflow from the channels to the surroundings than the inflow into the channel from the surroundings. The silting information in the channels supplemented by values of total recharge amount can be helpful for regulation of groundwater level in surroundings of the channels.

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