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4. Hydrogeologic Characteristic of the Podunajská Rovina Flat

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Abstract: The Podunajská rovina Flat (hereinafter Danubian Flat) represents one of the most important hydrogeological regions in Slovakia, situated in the Danube Basin. Its fill consists of alternating aquicludes (clays, claystones) and aquifers (sands, sandstones, gravels) of Neogene and Quaternary aquifers (gravel and sand), which are characteristic of intergranular permeability. The importance of the Quaternary aquifers is emphasized by the fact that they were deposited directly on the Neogene aquifers in a large part of the area of interest and often together they form a single aquiferous hydrogeological complex with ambiguous boundaries. The considerable thickness of the Neogene (max. 3,000 m) and the Quaternary (max. 600 m) sediments thus create conditions for significant accumulation of groundwater.

Key words: Groundwater, Danube, regime, level, coefficient of transmissivity, aquifer

4.1 Introduction

The favourable characterization of the Danubian Flat area from the point of view of its aquifers was of interest to local and regional hydrogeological works (about 3,000 wells), the aim of which was to obtain groundwater for a wide range of its exploitation, depending upon needs of society.

In the Žitný ostrov (Rye Island) area, the groundwater reserves, expressed in terms of the usable amount, reach approximately 20,500 $l.s^{-1}$ (Gavurník et al., 2012), which represents the largest reserves in Slovakia and the Central Europe. This part of the Danubian Flat is one of the largest protected water management areas in Slovakia. Favourable hydrogeological conditions of the area were also reflected in the implementation of six water sources, which are among the largest in Slovakia.

The groundwater circulation and regime *in the northern part of the Danubian Flat (north of the Little Danube River) and the southern part of the plain (the area between the rivers Little Danube, Danube and Váh, including the right bank of the Danube in the Slovak Republic)* differ significantly. In the northern part of the territory, the groundwater regime is mainly dependent on winter precipitation, coefficient of transmissivity and level of local rivers and groundwater transfer from neighbouring territories. In the southern part of the territory, the groundwater regime is dependent on the coefficient of transmissivity and status of the levels of the rivers Danube, Little Danube, Váh, their channels and river branch system. The operation of the Gabčíkovo and Kráľová nad Váhom water structures (Waterworks; hereinafter WW), which use the hydro-energetic, navigational and recreational potential of the two most watery surface streams (Danube and Váh) of the Danubian Flat, also affects the regime of surface- and groundwaters.

The hydrological axis of the area is formed by the Danube with a rich branch and channel system with most important branch of the Little Danube. The Váh River (with its mouth into the Danube in Komárno) with a left tributary of Nitra represents a significant water course of N-S direction. The streams of local importance are mainly represented by the left tributaries of the Little Danube, which drain the eastern slopes of the Malé Karpaty Mts. as well as the space between the mountain range and the Váh River (e.g. Čierna voda, Dudváh, Gidra).

In the Danubian Flat territory, cold mineral waters are found only in the area of Svätý Jur. On the other hand, this region is very important in terms of geothermal waters. Significant accumulations of geothermal waters are found in the sediments of the Neogene (the Danube Basin Central Depression) and the Mesozoic (the Komárno Marginal Block; article 5 of this volume). So far, the geothermal potential of the Danubian Flat has been verified through 38 geothermal wells.

In the territory of interest it is possible to distinguish hydrogeological units of Crystalline, Mesozoic, Neogene volcanics, sedimentary Neogene and Quaternary. The dominant part of the territory involves the Quaternary hydrogeological regions Q 051, Q 052 and Q 074 (Fig. 4.1).

Determination of hydraulic parameters of individual hydrogeological units was made mainly on the basis of evaluation of hydrogeological exploratory boreholes recorded in the Geofond archive of SGIDŠ.

4.2 Hydrogeologic region of the Crystalline

In the area of interest this unit is represented by a narrow stripe from Bratislava (Krasňany) to Svätý Jur and is built of granitoids, gneisses, migmatites, amphibolites, phyllites and schists. Tectonic failure determines the fissure permeability of the aquifer. More significant are transverse fissures and cracks, which are more open and therefore more permeable.

The mean value of the coefficient of transmissivity $T = 4.3 \cdot 10^{-5}$ $m^2.s^{-1}$ and the mean value of the coefficient of hydraulic conductivity $k = 4.8 \cdot 10^{-6}$ $m.s^{-1}$ (Hanzel et al., 1999) were determined for the Pezinok section of Malé Karpaty Mts. granitoids during the hydrogeological

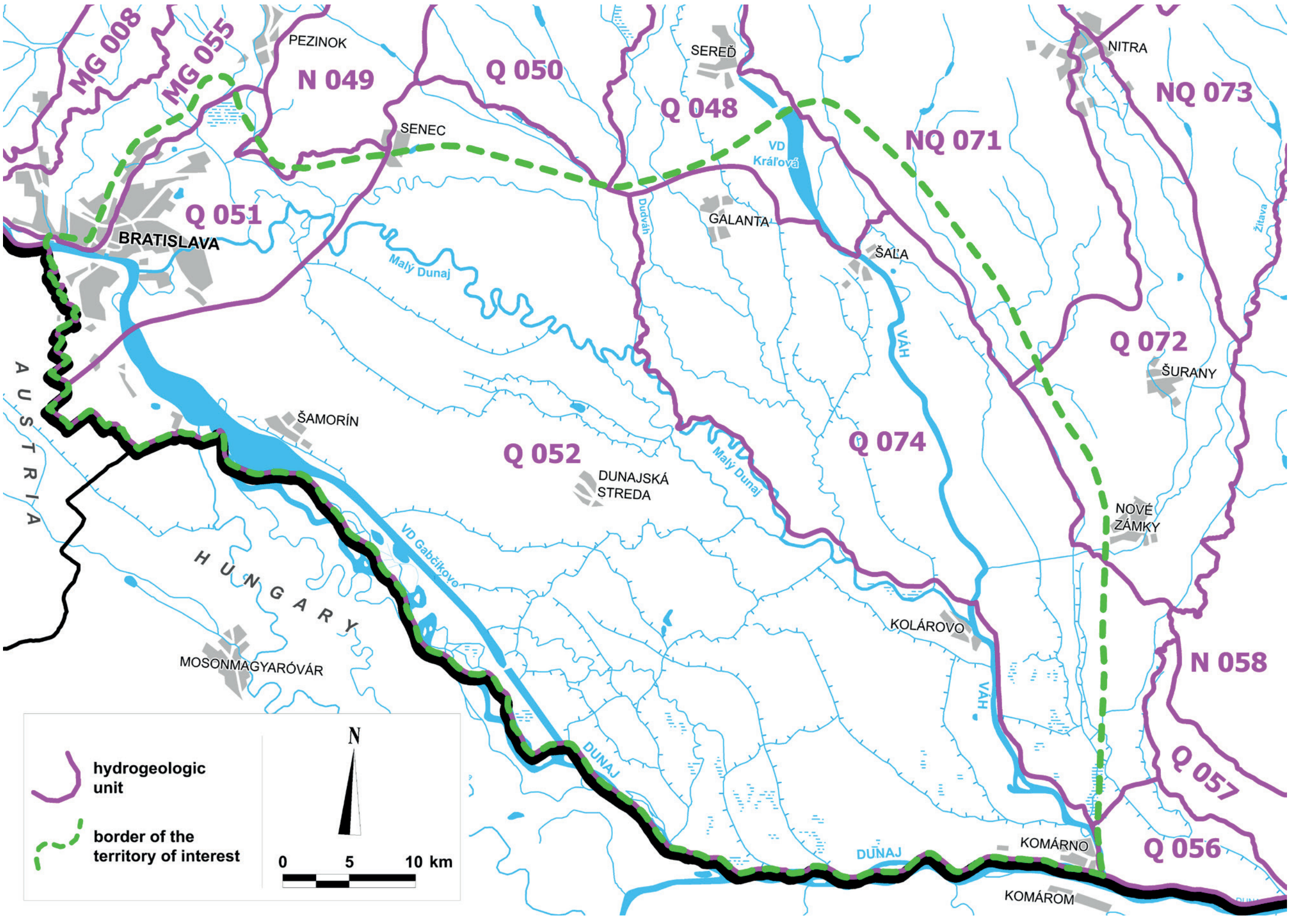

Fig. 4.1 Hydrogeological regions of the territory of interest (according to Šuba & Mihálik, 1998)

survey. The zone of weathering and near-surface loosening extends to a depth of 30 – 50 m below the ground. For crystalline schists, these values were slightly lower (T = 3.2 . 10^{-5} $m^2.s^{-1}$, k = 2.6 . 10^{-6} $m.s^{-1}$). It is obvious that these are rocks with low coefficient of transmissivity (Hanzel & Vrana, 1999).

Groundwater circulation in the granodiorite massif is limited. In particular, it is bound to the zone of weathering and near-surface disintegration of rocks, and therefore no significant accumulation of groundwater occurs. The yield of the springs is strongly influenced by atmospheric precipitation. Due to the strong influence of rainfall, the springs have a large range of yield. There are no significant springs surging from the granites of the Bratislava Massif. The yield of predominantly fissure and slope debris-fissure springs is 0.01 – 0.3 $l.s^{-1}$, sporadically 0.5 – 1.0 $l.s^{-1}$. The direct passage of groundwater from the Malé Karpaty Mts. to the sediments of the neighbouring Danube Lowland may occur at alluvial cones in places with suitable hydraulic properties.

The basic mineralization process forming the chemical composition of the groundwater of the Malé Karpaty Mts. Crystalline is the hydrolytic decomposition of the silicate minerals present. This process causes the formation of a chemical composition of A_2 type water predominantly, indistinct Ca-Mg-HCO_3 with low TDS in the range of 0.17 – 0.41 $g.l^{-1}$ with an average value of 0.25 $g.l^{-1}$ (Rapant et al., 1993). The knowledge of the isotopic composition of the groundwater of this hydrogeological unit is scarce and therefore we do not discuss it.

4.3 Hydrogeological region of the Mesozoic

Mesozoic aquifers were verified in the south-eastern part of the territory in the Komárno area by geothermal borehole M-1 (Pagáč & Čermák, 1976), geothermal borehole M-3 (Franko & Račický, 1979) and geothermal borehole FGK-1 (Remšík & Franko, 1978). The boreholes penetrated into the carbonates of the Transdanubian Mountains of the Pelsö unit from a level of about 1,100 or 1,700 m b.s. These are mainly limestones, dolomites and dolomitic limestones of the Late Triassic to Jurassic, which represent important aquifers with fissure-karst permeability. The rate of overflow on borehole collars was about 1.6 – 5.3 $l.s^{-1}$ at groundwater temperature at 42 – 64 °C. Coefficient of transmissivity fluctuates in interval T = 5.1 . 10^{-5} – 2.2 . 10^{-4} $m^2.s^{-1}$.

The geothermal water in the Komárno Marginal Block is likely to accumulate in a closed hydrogeothermal structure that does not have an infiltration and surge area. From a chemical point of view, it is a mixed type of water with a predominance of Ca-SO_4 component and an increased content of Na-Cl with mineralization of about 2.2 – 3.1 $g.l^{-1}$ (Remšík et al., 1992).

Kantor et al. (1985) states for well M-3 water $\delta^{18}O$ = -12.58‰. The water is of meteoric origin, probably infiltrated in a period of colder climate.

4.4 Hydrogeologic region of Neogene volcanics

The main fill of the whole Danube Basin, which has a bowl-shaped brachysyncline structure, consists of brackish and freshwater sediments of the Late Miocene and Pliocene; in their bedrock occur Langhian – Serravallian and Sarmatian marine and brackish sediments, or buried volcanic centres.

The oldest Neogene beds of the *Langhian* age – Šurany volcanites (andesites) were verified by geothermal borehole HGB-1 Rusovce at a depth of 1,027 – 1,259 m (Bondarenková, 1977). Pre-Cenozoic bedrock was also verified in their basement. These are Palaeozoic amphibolites of the Malé Karpaty Mts. with horizons of quartzose diorite and aplitic gneisses, drilled in the interval 1,259 – 1,493 m.

The interval of Langhian – Serravallian andesites was hydraulically tested by an open section of 1,100 – 1,124 m. By a hydrodynamic test in year 1982 the following values of yield and draw-down were found on the well: 0.5 $l.s^{-1}$/24.0 m; 0.8 $l.s^{-1}$/46.0 m; 1.08 $l.s^{-1}$/60.0 m. Since the envisaged location of the Serravallian clasts was not verified by the borehole, further hydrodynamic tests were not recommended due to low yield of a overflow (0.01 $l.s^{-1}$), low water temperature (15 – 25.4 °C), deep operating level, presence of methane and H_2S. The tested aquifer horizon was assessed as negative from the perspective of the further use of geothermal waters and the well was discarded. The coefficient of transmissivity of the Langhian – Serravallian aquifer from the HGB-1 borehole was determined T = 1.1 . 10^{-5} $m^2.s^{-1}$ and the coefficient of hydraulic conductivity k = 4.9 . 10^{-7} $m.s^{-1}$, whereby the aquifer was classified as poorly permeable.

From the chemical point of view it is fossil sea water of the Na-Cl (SO_4) type with mineralization of 17 – 23 $g.l^{-1}$. Water has a relatively high content of $SO_4/S_1(SO_4)$ (16.08%), CO_2 (206.8 $mg.l^{-1}$), H_2S (59.86 $mg.l^{-1}$), a ratio of Na : K = 33.1, SO_4 and HCO_3 as well as the presence of Br and I (Hanzel et al., 2012). No data on the isotopic composition of water are known from this hydrogeological unit.

4.5 Hydrogeologic region of the sedimentary Neogene

The thickness of the Neogene sediments in the central Gabčíkovo Depression reaches 3,500 m. These are predominantly clays and sands deposited in the lacustrine and delta environment. Groundwater of sedimentary Neogene verified by hydrogeological wells in the area of interest is bound to aquifers in the Serravallian – Pliocene range. The Neogene surface crops out in the vicinity of Bernolákovo, Chorvátsky Grob and Pezinok.

The hydraulic properties of deeper-lying sands to weakly cemented sandstones of Pliocene and Pannonian Tortonian) are known from geothermal wells (about 1,000 – 2,500 m deep) from the Central Depression of the Danube Basin. The clays act as aquicludes. The yield of overflow wells was 0.3 – 25.0 $l.s^{-1}$ (Fendek & Bodiš, 1992). Values of the coefficient of transmissivity lie in the interval T = 9 . 10^{-5} – 2.6 . 10^{-3} $m^2.s^{-1}$ with an average value of T = 5.3 . 10^{-4} $m^2.s^{-1}$, the average values of the coefficient of hydraulic conductivity were set to = 9 . 10^{-7} – 3 . 10^{-5} $m.s^{-1}$ with a mean value of 6.7 . 10^{-6} $m.s^{-1}$. The tested sections thus represent, on average, aquifers with moderate or medium coefficient of transmissivity. From a chemical point of view, it is predominantly water of the Na-HCO_3 and Na-HCO_3-Cl type with a TDS in the interval of 0.5 – 8.3 $g.l^{-1}$ (Jetel et al., 2012).

Shallower hydrogeological exploratory boreholes verified sand and gravel positions of Sarmatian (Serravallian) to Pliocene, and less frequent Zanclean.

In the shallower part of the Neogene there is documented (Bottlik et al., 2013) water coming from precipitation of the colder period ($\delta^{18}O$ from -12.19‰ to -13.90‰, δ^2H from -89.5‰ to -101.0‰). At deeper levels, $\delta^{18}O$ ranges from -13.8‰ (colder rainfall water) to -1.98‰ (sea water). The transient values of $\delta^{18}O$ are the result of mixing these two types of water (Kantor, 1985, Michalko, 1998, Franko, 2001). The residence time (^{14}C) for the water of individual wells ranges from 26,000 to 42,000 years (Franko et al., 1995, Franko, 2001).

In the <u>northern part of the Danubian Flat</u>, the Sarmatian (Serravallian) clay-sandy locations of the Vráble Formation were assessed by Schwartz et al. (2004). In the bedrock of the Quaternary sediments the formation forms a narrow strip following the mountains of the Pezinok Carpathians between Nižná and Pezinok. In the vicinity of the Bratislava-Vajnory suburb this complex overlies directly the crystalline bedrock. The average coefficient of transmissivity was determined T = 8.70 . 10^{-4} $m^2.s^{-1}$.

Ivanka clay-sandy Fm. of the Pannonian crops out around Pezinok. A greater number (more than 4) of sandy aquifers were found in the Vajnory – Slovenský Grob area. At the locality Chorvátsky Grob, the Fm. was verified by the structural geological borehole FGB-1 at the level of 348 – 437 m b.s. and in the borehole G-1 at the level of 240 – 480 m b.s., at the site Bratislava – Martanovičova Street in the borehole Ma-1 of 195.0 – 196.5 m b.s. The average value of the coefficient of transmissivity was determined T = 6.46 . 10^{-4} $m^2.s^{-1}$.

The *sediments of the Beladice Formation (Pannonian, Pontian)* are made up mainly of clay with layers of sand and lignite, in the marginal part they are represented by sands and sandstones. They crop out to the surface in the vicinity of Bernolákovo and Chorvátsky Grob. The sands and sandstones are cross-bedded and contain clay galls (Koutek & Zoubek, 1936 in Bottlik et al., 2013). The average number of aquifers in the Senec – Šenkvice – Chorvátsky Grob area is 2 to 4. On the basis of hydrodynamic tests, the average value of the coefficient of transmissivity was determined T = 5.986 . 10^{-4} $m^2.s^{-1}$.

The *Volkovce Formation of Zanclean* is built of colourful clays in which gravel and sand horizons are located, and sporadic lignite intercalations and lenses. South of the Galanta – Kajal – Horný Jatov line, the formation submerges below the Pliocene sediments (the Kolárovo Fm.). The complex is characterized by intergranular permeability and often confined groundwater, creating so an artesian horizon. At the top of the Zanclean the positions of sand with gravel are more and more frequent. In the central part of the depression, the data on the gravel position is absent, formed by an irregular alternation of sand and clay. Number of aquiferrous sandy horizons in the Senec area is mostly 2 – 4. In the area of Šaľa – Trnovec nad Váhom, the number of aquifers is 3 to 5. The greater number (more than 5) of aquifers was found in Nové Zámky. The regional evaluation documented the second highest average value of the coefficient of transmissivity for the sands of this layer T = 1.219 . 10^{-3} $m^2.s^{-1}$.

The *Kolárovo Formation of Pliocene* – the youngest Neogene hydrogeological unit, is the most permeable within the complex of the Neogene basinal structures. The formation consists of mica-rich sand and fine gravel alternating with strongly sandy grey, rusty and greenish clay, occasionally calcareous. The layer thickness is 100 – 150 m (Vass, Nagy & Elečko in Tkáčová et al., 1996). The Neogene hydrogeological subunit does not crop out to the surface in the area studied. The number of aquifers in the Vlčany – Komoča – Andovce – Palárikovo area is mostly 2 to 4. In the area of Sládkovičovo – Čierny Brod – Horné Saliby the number of aquiferrous sandy and sandy-gravelly horizons is 1 to 2. Greater number of aquifers (more than 4) were discovered in Galanta – Kajal. The sands and gravels of the Kolárovo formation deposited in the Latest Pliocene have an average coefficient of transmissivity T = 1.697 . 10^{-3} $m^2.s^{-1}$ (Bottlik et al., 2013).

In the southern part of the Danubian Flat the exploration boreholes in the SE parts of Žitný Ostrov (in the area between Číčov, Okoč and Kolárovo) verified permeable Neogene sandy horizons at the level of 19 – 280 m. According to the Danreg 1: 200,000 Quaternary sediment map of genetic types and thicknesses, the Quaternary overlying layer of Neogene reaches a thickness of 10 – 50 m (Pristaš, Tkáčová et al., 1998 in Scharek et al., 1998). The depth of the assessed boreholes is 19 – 280 m (113 m on average), the length of the verified sections reaches 2 – 56 m (18 m on average), which is an average of 18% of the total borehole depth. From the evaluation of the number of sandy, or gravel aquifers alternating with clay Neogene aquicludes it follows that the largest number of boreholes verified one to four permeable horizons (44 boreholes) in their profiles and 11 boreholes verified five to ten positions of aquifers.

On the territory of the Žitný Ostrov (Rye Island), the hydrogeological unit of the Neogene is characterized by the average value of the coefficient of transmissivity T = 6.1 . 10^{-3} $m^2.s^{-1}$ (2nd class of transmissivity, sensu Krásny, 1986). The average value of the coefficient of hydraulic conductivity k is 3.1 . 10^{-4} $m.s^{-1}$. The specific yield of wells q fluctuates in the range of 0.02 – 21.98 $l.s^{-1}.m^{-1}$ (average value of q is 3.0 $l.s^{-1}.m^{-1}$). Variability of the coefficient of transmissivity – the spatial inhomogeneity of the aquiferous rock environment, which is characterized by the standard deviation of the coefficient of transmissivity index Y s_Y (0.72), assigns this whole to a largely inhomogeneous hydrogeological environment with great variability.

In seven wells, the depth of which was predominantly above 100 m, artesian horizons with a positive artesian pressure were verified during the exploratory work, i.e., positive overflows were recorded on wells. These are boreholes HgK-3 Komárno (180 m), HGL-1 Veľký Lél (170 m), HG-Zl Zlatná na Ostrove (163 m), HVČ-2 Štúrová (142.5 m), HGP-2 Komárno (150 m), HP-1 Komárno (200 m) and S-1 Nová Stráž (71 m). The highest yields were verified by borehole HVČ-2 Štúrová (Šarlayová, 1986), the borehole depth was 142.5 m; filter at 92 – 138.5 m; verified maximum drilling capacity of 52.63 $l.s^{-1}$ at a drawdown of 2.29 m. Another highly productive horizon was confirmed by the HVK-1 Kameničná (Šarlayová, 1986) well, the well depth was 111.0 m with the open part of the well at a level of 54 – 110 m with yield values of 31.25 $l.s^{-1}$ at a drawdown of 2.38 m as well as in other boreholes, especially around Kolárovo, Zemianska Olča and Číčov.

In the sense of the lithological division of the Neogene, the boreholes were compared, which in their filter parts captured only sand (42 wells), sandy gravel and sand (10 wells), or only sandy gravel (3 wells). Comparing the calculated statistical parameters, the highest average coefficient of transmissivity rate for gravel (T = 2.51 . 10^{-2}.$m^2.s^{-1}$) was confirmed, lower for gravel and sand (T = 8.43 . 10^{-3} $m^2.s^{-1}$) and the lowest for sands (T=8.84 . 10^{-4} $m^2.s^{-1}$). The average specific yield q in boreholes verifying Neogene gravels was 8.10 $l.s^{-1}.m^{-1}$, in boreholes with gravel and sands 6.85 $l.s^{-1}.m^{-1}$ and in boreholes verifying only Neogene sands 1.71 $l.s^{-1}.m^{-1}$ (Benková et al., 2005).

4.5.1 Circulation and regime of groundwater in Neogene sediments

Due to lithology and tectonics, the circulation and groundwater regime in Neogene sediments are complex. In all Neogene complexes, impermeable clay positions alternate with permeable sandy or gravel horizons. Favourable conditions for the emergence of aquifers (artesian) horizons were created in the of Miocene and Pliocene facies, where the thickness of sandy horizons often reaches several meters. Their horizontal and vertical distribution is uneven, the positions of the permeable layers often wedge out and form lens-like bodies. The occurrence of aquifers is not regular and their interconnection is complicated, resulting in a significant anisotropy of the permeability properties in both the vertical and horizontal directions. The yield of wells, which have been verified by Neogene aquifers, varies considerably – from 0.1 up to several litres per second. The realization of boreholes was motivated by the need to search for groundwater at greater depths due to lack of yield or poor water quality in Quaternary sediments.

4.5.2 Hydrogeochemical properties of groundwater of Neogene sediments

From the hydrogeochemical point of view, groundwater bound to Neogene aquifers can be characterized as carbonatogenic water A_2 of a distinct type with mineralization in the range of about 306.47 – 1,059.7 $mg.l^{-1}$ with a mean value of 530 $mg.l^{-1}$. In the profile of the Neogene sediments towards the depth it is possible to observe a characteristic continuous transition of the chemical composition of water from the Ca-(Mg)-HCO_3 type to the Na-HCO_3 type. These changes are related to changes in thermodynamic, oxidation-reducing and partly hydrodynamic conditions of circulation. Apart from the increased iron content (less manganese), the groundwater with shallow circulation in the Pontian or Pannonian usually meets the criteria of the drinking water standard. The frequent increased content of ammonium ions and phosphates is mostly of primary origin (biochemical decomposition of organic substances, or dissolution of accessory apatite present in the aquifer horizons) (Bottlik et al., 2013).

The meteoric origin of groundwater of shallow sedimentary Neogene was documented on the basis of knowledge of the isotopic composition of hydrogen and oxygen. In the wider area of Galanta, Šaľa, Vlčany, Palárikovo and Nové Zámky, in the samples from boreholes with confined water the values $\delta^{18}O$ from -12.19‰ to -13.90‰ and $\delta^{2}H$ from -89.5‰ to -101.0‰ were documented (Bottlik et al., 2013). Groundwater with such an isotopic composition cannot be derived from current rainfall, it had to infiltrate during a period of colder climate at higher altitudes and should be expected to have a higher residence time. The presence of this water in the area is the result of transfer from nearby mountain ranges or is mediated by palaeo-streams. Different isotopic composition of groundwater from artesian borehole near the church in Veľký Biel – borehole no. 520 with $\delta^{18}O$ = -10.27‰ and $\delta^{2}H$ = -74.3‰ (Bottlik et al. 2013) confirms the presence of groundwater from current local precipitation.

4.6 Hydrogeologic region of Quaternary

Of the total number of genetic types of Quaternary sediments, fluvial accumulation in the stratigraphic range from the Lower Pleistocene to the Holocene dominates in the area. The highest thicknesses (up to 500 m) are reached in the central part of the Danube Basin – in the Gabčíkovo Depression, where they are deposited in superposition facies, based on locally preserved transitional fluvio-lacustrine strata (Upper Pliocene/Lower Pleistocene).

Aquicludes with low intergranular permeability include positions of Quaternary aeolian sediments (loess). Deluvial, proluvial and organic sediments are characterized by relatively low permeability. Quaternary fluvial sediments and anthropogenic sediments have a high permeability.

The average value of the coefficient of transmissivity of the main fluvial formation in the northern part of the Danubian Flat was determined to be $T = 1.55 \,.\, 10^{-2}\ m^2.s^{-1}$, higher in the southern part of the plain in the Žitný ostrov area $T = 5.45 \,.\, 10^{-2}\ m^2.s^{-1}$ and the highest value in the right bank of the Danube $T = 8.97 \,.\, 10^{-2}\ m^2.s^{-1}$.

<u>In the northern part of the Danubian Flat</u> there are seven hydrogeological sub-units. These are anthropogenic, organic, deluvial, fluvial, aeolian, proluvial sediments and fluvial sediments of the middle terraces.

Anthropogenic Holocene sediments of landfill type occupy a small area in the evaluated area. These are the youngest Quaternary deposits that are the product of human activity. They are characterized by intergranular permeability of considerable variability and heterogeneity due to the diverse nature of the deposited material. Based on the processing of permeability parameters for the Integrated Landscape Management (IMK) (Malík et al., 2007), an average coefficient of transmissivity value $T = 2.62 \,.\, 10^{-3}\ m^2.s^{-1}$ the anthropogenic sediments was assigned.

Organic sediments are represented in the area by peats and humus-rich peat clays, *Holocene in age*. Sediments of marsh swamps and peat bogs were formed in local marsh depressions, or older oxbows, in the overburden of low permeable to impermeable clayey and loamy flood plain sediments. The organic sediments are characterized by their own specific groundwater circulation system. They are most often bound to wetlands. From a hydrogeological point of view, these sediments have no practical use due to the low accumulation and groundwater quality. In the northern part of the Danubian Flat in the cadastral area of the municipality Svätý Jur there is a National Nature Reserve Šúr, which occupies the territory of the former Pleistocene lake. In the area of the Malé Karpaty Mts. it is the largest preserved peat bog. It is a part of several peat bogs that have been formed within Neogene depressions. The organic sediments have intergranular permeability and serve as a aquifer. There are no hydrogeological boreholes in the assessed area in the organogenic sediments, but on the basis of the results processing in the IMK project (Malík et al., 2007) the average value of the coefficient of transmissivity was determined for this whole by a qualified estimate $T = 4.52 \,.\, 10^{-4}\ m^2.s^{-1}$.

Deluvial sediments – loamy-clayey and sandy slopes of the Pleistocene – Holocene age create more continuous areas in the western part of the studied area in the foothills of the Malé Karpaty Mts. They consist of lithofacies of undistinguished slope debris (mainly sandy and clay colluvial loams, outwash loams, sandy clays with fragments, fine-grained sands and loess runoffs, loamy-stony and sandy-stony sediments and deluvial re-deposited sands). The sediments are characterized by intergranular permeability. Their hydrogeological character is determined by the nature of their bedrock. Based on the results of the IMK geological task (Malík et al., 2007), the value of the coefficient of transmissivity deluvial sediments based on the evaluation of the results of hydrodynamic tests was assigned to $T = 9.71 \,.\, 10^{-5}\ m^2.s^{-1}$.

Fluvial sediments of the bottom accumulation in the low terraces of the Upper Pleistocene – gravel, sandy gravel and sands mostly covered with loam occupy the most extensive and coherent area in the region. Almost all parts of the Podmalokarpatská pahorkatina Hummocks, the Trnava Table between Veľký Grob and Pusté Úľany and the Nitra Table between Močenok and Jatov cover the rest of the other areas of the Danubian Flat and the remaining table parts of the Uplands. However, due to their coverage, by younger – Holocene fluvial deposits (clays and sandy clays) of the flood-plain facies, most sediments of so-called *bottom accumulation* do not crop out to the surface. The pumping tests were mainly used to explore the bottom accumulations in the floodplains, which are a very important aquifer of groundwater and hydrogeological boreholes are situated in them quite often. The value of the coefficient of transmissivity T was determined in the range from 5.03 . 10^{-1} $m^2.s^{-1}$ to 2.12 . 10^{-4} $m^2.s^{-1}$, the mean value is T = 1.55 . 10^{-2} $m^2.s^{-1}$.

Fluvial Pleistocene sediments of middle terraces – sandy gravel and gravel through areas covered with loess and outwash deposits attain only small areas, where in the form of morphologically significant degree (edges) of the lower middle terrace they border almost the entire southern edge of the Trnava Table between Veľký Grob and Pusté Úľany and SW rim of the Nitra Table between Močenok and Jatov. Groundwater bound to gravel and sandy gravel of the middle terraces is fed by infiltration from rainfall or by hidden passages from surface streams. The groundwater table level is therefore deeper below the terrain and has a more variable oscillation than fluvial alluvia. In the monitored area the sediments of the middle terraces show about one order, i.e. 10 times lower values of hydraulic conductivity parameters compared to the parameters of fluvial the sediments. Based on the processing of the results of hydrodynamic tests, the fluvial sediments of the middle terraces was assigned a coefficient of transmissivity T = 1.104 . 10^{-3} $m^2.s^{-1}$.

Aeolian sediments – loess and loess loams of Pleistocene are the dominant cover formation in the Trnavská pahorkatina Upland. They occur in the northwest part of the area studied. Due to their granulometric characteristics, they are very poorly permeable and have the character of a regional hydrogeological aquiclude. In loess, a relatively coarse unsaturated zone is developed, and the groundwater level is often deeper. Based on the results of Schwarz et al. (2004) the sediment was assigned value T < 1 . 10^{-6} $m^2.s^{-1}$.

Proluvial sediments of alluvial cones (loamy to sandy-loamy gravels) developed in the region of the stratigraphic range of the Lower – Upper Pleistocene and preserved especially at the foothills of the Malé Karpaty Mts. in the zone of their contact with the Danubian Flat and Trnavská pahorkatina Upland from Bratislava-Rača through Svätý Jur, till Modra. They are also developed on large areas of the Podmalokarpatská pahorkatina Upland between Pezinok, Šenkvice, Chorvátsky and Slovenský Grob. They often reach the territory of the hills far from the mountains, as well as under loess in the area of contact between the Podmalokarpatská pahorkatina Upland and the Trnava Table. The edges of the largest cones are covered with aeolian loess, aeolian-deluvial loess loam and deluvial outwash. The proluvial sediments are characterized by intergranular permeability. Their important hydrogeological function is to allow direct passage of water from the mountainous areas to the lowland sediments. The surface flows on the proluvial sediments are characterized by reduced flow rates or they completely diminish. Based on a regional evaluation of hydraulic parameters, the proluvial sediments was assigned a coefficient of transmissivity T = 8.494 . 10^{-4} $m^2.s^{-1}$ (Bottlik et al., 2013).

From the hydrogeological point of view, *in the southern part of the Danubian Flat (in the Žitný ostrov and the right bank of the Danube)* we can observe almost homogeneous representation of the dominant Quaternary aquifer, the fluvial sediments of the Pleistocene – Holocene – sandy gravel.

In order to assess the depth dependence of the hydraulic parameters, the boreholes were divided into three groups according to the location of the filter within 25.0 m; in the intervals of 25.0 – 50.0 m and 50.0 – 100.0 m. As a result, it is found that in terms of hydraulic parameters in the range of 0.0 – 100.0 m b.s. there are minimal differences within the order. The mean value of the coefficient of transmissivity T is the lowest in the upper interval 0 – 25 m b.s. T = 1.93 . 10^{-2} $m^2.s^{-1}$ and the highest in the lower interval 50 – 100 m b.s. T = 2.41 . 10^{-2} $m^2.s^{-1}$. In the mean interval of 25 – 50 m the mean value of T = 2.31 . 10^{-2} $m^2.s^{-1}$.

The *spatial dependence of hydraulic parameters* in the area of interest was investigated in 4 areas – in the right bank of the Danube, in the upper part of Žitný ostrov, in the central part of Žitný ostrov and in the lower part of Žitný ostrov. The Žitný ostrov area was schematically divided according to Quaternary isolines to 100 m, i.e. in the west by the Hamuliakovo-Dunajská Lužná-Zlaté Klasy line and in the east by the Kľúčovec-Čalovo-Topoľníky line.

From the comparison of hydraulic parameters, the highest average coefficient of transmissivity was verified in the right bank of the Danube T = 8.97 . 10^{-2} $m^2.s^{-1}$, in the central part of Žitný ostrov T = 8.03 . 10^{-2} $m^2.s^{-1}$ and in the upper part of Žitný ostrov T = 7.17 . 10^{-2} $m^2.s^{-1}$. The lowest average coefficient of transmissivity value was determined in the lower part of Žitný ostrov T = 1.14 . 10^{-2} $m^2.s^{-1}$.

The highest yields of the Quaternary aquifer were verified by boreholes (with a diameter of the final borehole approx. 300 – 400 mm) at the Bratislava-Mokraď localities by the HM-1 borehole (borehole depth 64.0 m). the proportion between the pumped amount and the drawdown was Q/s – 170.0 $l.s^{-1}$/0.7 m; Dunajská Streda – borehole HDS-2 (borehole depth 80.0 m), Q/s – 209.8 $l.s^{-1}$/0.92 m; Šamorín – borehole HGŠ-1 (borehole depth 67.0 m), Q/s – 117.0 $l.s^{-1}$/0.67 m; Bratislava-Rusovce-Mokraď – borehole ST-17 (borehole depth 77.5 m), Q/s – 220.0 $l.s^{-1}$/1.95 m; Čunovo – borehole HVZ-50 (borehole depth 29.0 m) – Q/s – 117.0 $l.s^{-1}$/0.58 m, as well as at the sites Kvetoslavov, Hviezdoslavov, Baka, Gabčíkovo, Podunajské Biskupice and Eliášovce (Benková et al., 2005).

4.6.1 Groundwater circulation and regime in the Quaternary sediments

The *groundwater regime* in the Danubian Flat is monitored through the SHMI monitoring network, which consists of approximately 350 observation wells. The circulation and regime of groundwater in the northern region of the Danubian Flat is dependent on winter precipitation, coefficient of transmissivity and water level of rivers (Danube, Little Danube, Čierna voda, Dudváh and Váh) and groundwater transfer from neighbouring territories (Trnavská pahorkatina Upland, Nitrianska pahorkatina Upland, Malé Karpaty Mts.).

In the southern part of the Danubian Flat, the groundwater regime is dependent on the coefficient of transmissivity and the state of river levels (Danube, Little Danube and Váh) and their channels.

The precipitation and groundwater regime *in the northern area of the Danubian Flat* has a significant impact on groundwater replenishment, which can be observed in plain areas outside near-river zones. The meteoric water supply in these areas is evidenced by regime measurements of groundwater table levels, according to which groundwater supplies are replenished and levels rise already in the winter months, i.e. when the surface streams still have minimal levels. It is mainly due to climatic factors, the ratio of evaporation and precipitation. As a result, rainfall is substantially infiltrated in the winter months, aided by lack of plant cover, flat relief and overburden character (Bujalka et al., 1967). The course of groundwater fluctuations shows that in periods with low rainfall in the winter months there was a steady decline in groundwater levels, even though summer sums were normal or even elevated. Years with a high winter total always mean a significant rise in groundwater levels, even though the yearly total is normal (Bodiš et al., 1998).

Surface water infiltration from the Danube to gravelly sediments is already occurring in the area of Bratislava, where the general direction of groundwater flow is W-E or NW-SE. In the northern part of the Danubian Flat, the groundwater is supplied also by hidden inflows from the Trnavská pahorkatina Upland. In the Pusté Úľany and Sládkovičovo areas the direction of groundwater flow from the north to the south was found, which later turns to the NNW-SSE. According to Bujalka et al. (1967) in the area between Kráľová pri Senci, Veľké Úľany and Jelka, the groundwaters from three directions W-E, NW-SE and in direction N-S meet together.

The impact of the Little Danube on groundwater is only negligible and extends only to the riverbed area. The direction of groundwater flow in this area is along the Little Danube (Bujalka et al., 1967). The flow of Čierna voda is dependent on the state of groundwater levels. Outside the narrow belt along the Little Danube, the infiltration of the meteoric water in winter (November-March) is decisive for the groundwater replenishment of the area. In the area of Veľké Úľany – Čierny Brod there is a direction of groundwater flow from NW to SE. In the area of Kráľová pri Senci – Veľké Úľany – Jelka, the intersecting groundwaters from the Trnavská pahorkatina Upland meet the groundwater flow from the Danube, which is also reflected in the yields of individual sources.

The area around Jelka is supplied by groundwater flow of NW-SE direction at any groundwater level including extreme minimum and maximum. The extent of the territory involved in its supply is determined by groundwater levels – the lower the levels, the greater the impact of depression. Groundwater flows from the territory of the villages Kráľová pri Senci, Kostolná pri Dunaji, Hrubá Borša, Jelka, Jánovce and their surroundings; in the general direction of groundwater flow are also villages Hrubý Šúr and Hurbanova Ves (Takáčová et al., 2002).

In the northern part of the Danubian Flat, groundwater was supposed to be associated with the territory of Žitný ostrov (Takáčová et al., 1969). The evaluation of the groundwater regime in the wider surroundings of the Jelka water source for the years 1985 – 1990 (Vojtko in Takáčová et al., 2002) states that the impact of the main Danube River in the replenishment of groundwater reserves in the area of interest must be accepted, although the distance and other factors operating around the water source play their roles. The hydraulic connection of the surface flow of the Danube with groundwater in the area of the Jelka water supply was clearly demonstrated by the filling of the Gabčíkovo Waterworks, which started on 26 October 1992. The damming of the Danube and the filling of the reservoir resulted in rising groundwater levels. Since that time, groundwater levels in the Jelka water source have been higher than before the Gabčíkovo Waterworks were commissioned and put into operation (Takáčová et al., 2002).

The direction of groundwater flow in the fluvial sediments of the Váh River is parallel to the Váh River in the area and shows its infiltration effect. In the stretch of alluvia between Vinohrady nad Váhom and Galanta, the influences of Váh, rainfall and transfers from the Trnava and Nitra Uplands are overlapping (Bujalka et al., 1967).

In the northern part of the area of interest there are also wetlands where the groundwater level is close to the terrain surface. In the direction from the west there are Šúr Wetland, Úľanská mokraď Wetland, Salibská mokraď Wetland, Martovská mokraď Wetland and Novozámocké pláňavy Plains.

The Šúr *Wetland* is located near Svätý Jur in an area with a thin cover of Quaternary sediments (2 – 5 m at the edge of the structure and 5 – 10 m at its centre), in which the Neogene impermeable sediments of a bowl structure occur (Maglay et al., 2007 in Malík, et al., 2007). The circulation and regime of groundwater is dependent on precipitation totals and the yields of flows from the Malé Karpaty Mts.

The Úľanská mokraď Wetland is located between Veľký Grob and Sládkovičovo, where Quaternary fluvial sediments of the terrace gravels with a thickness of 2 – 5 m are deposited upon an impermeable bedrock built of Neogene sediments (Maglay et al., 2007 in Malík, et al., 2007). Groundwater circulation and regime are influenced by rainfall totals and groundwater inflows from terrace gravels on its northern edge.

The *Salibská mokraď Wetland* extends in a narrow stripe from Galanta to Kolárovo between the rivers Váh and Stará Čierna voda. The *Martovská mokraď Wetland* in the lane from Trnovec nad Váhom to Patince between the river Váh and Dlhý and Patinský channels. To the east of the Martovská Wetland the *Novozámocké pláňavy Plains* are situated. All three wetlands are located on the edge of the Central Depression of the Danube Basin, where the bedrock is formed by sunken Neogene blocks. In the Salibská mokraď Wetland the thickness of the Quaternary sediments ranges from 15 to 60 m, in the Martovská mokraď Wetland from 10 to 20 m and in the Novozámocké pláňavy Plains from 10 m to 30 m (Maglay et al., 2007 in Malík, et al., 2007).

The circulation and groundwater regime in the Salibská mokraď Wetland is dependent on surface water flow and from the transfer of groundwater from the territory of Šaľa – Tešedíkovo, where the depth of the Quaternary bedrock rises from 30 m to 15 m (Maglay et al., 2007 in Malík, et al., 2007). The circulation and regime in the Martovská mokraď Wetland and in the Novozámocké pláňavy Plains are dependent upon the total precipitation and the transfer of water from the terrace sediments on their eastern edge.

In 1985 in the section between Sereď and Šaľa the WW Kráľová was completed with an area of 10.9 km^2 with a backwater length of 19.7 km and a depth of accumulated water up to 15 m. The WW is a part of the system of the dams of the Váh Cascade and it was built for the purpose of energy utilization of Váh, protection of the adjacent area against floods, for water abstraction for irrigation, navigability of the Váh section, fishing, water sports, recreation. The main WW objects are a water stage containing a weir, a hydroelectric power plant and a lock and a flat-type reservoir with perimeter levees and intake objects. The power plant with two generators has a total installed capacity of 45 MW with an average annual electricity production of 117.3 GWh. The tightness of the reservoir is ensured by loose perimeter levees and clay-cement underground sealing wall.

Prior to the reservoir filling, the Quaternary groundwater regime was characterized by short-term replenishment and long-term drainage. The regime observations carried out from 1957 until the filling in 1985 at the Váhovce object show that the natural regime was characterized by a characteristic downward trend. After the water reservoir was filled in 1985, there was a steady increase in water levels, especially in the vicinity of the reservoir, for example in the village of Váhovce about 1.20 to 2.50 m. In the adjacent area, groundwater is delayed due to the sealing wall, slowing down its flow and causing it to rise (Bodiš et al., 1998).

The key factors influencing the groundwater level oscillation in the Quaternary aquifer *of the southern part of the Danubian Flat* are mainly the water level in the old Danube riverbed from Bratislava to Komárno as well as the water level in the Čunovo reservoir, regime in the river branch system, WW Gabčíkovo, handling of drainage and irrigation systems, local influence of water sources exploitation and pumping of groundwater within the hydraulic curtain near Slovnaft.

The general direction of groundwater flow is mostly parallel to the main streams in the area (Danube, Little Danube). Local deviations are around the Slovnaft hydraulic curtain where the flow direction is changed from the Danube to the centre of the artificial groundwater depression. Rainfall affects the groundwater regime in the study area, especially in the summer half, when it affects the increase in yields in the surface streams in the territory and consequently also the increase of groundwater table level with different delay interval depending on distance from surface flow. Within the areas near the Danube the groundwater level oscillation follows the fluctuations in the Danube. At greater distances from the Danube, groundwater level change depends on seasonal effects and on the relationship between precipitation, including snow melting and evaporation from the ground and vegetation. The network of irrigation channels and drainage systems has a stabilizing effect on the groundwater table level.

In the southern part of the area of interest there are wetlands (in the west direction Potônska mokraď Wetland, Čiližská mokraď Wetland, Okoličnianska mokraď Wetland), where the groundwater level is close to the terrain surface.

The area between the *Potônska mokraď Wetland* and the Klátov Oxbow of the Little Danube is drained by the Starý Klátovský Channel, the Klátovský Channel and the Klátov Oxbow.

The Klátov Oxbow is about 25 km long. It is protected along the entire length of the stream as a National Nature Reserve. It surges gradually behind the village Orechová Potôň-Lúky. The upper section of the oxbow does not have a continuous level, it consists of a series of lakes. Around the settlement Csótfa the oxbow takes on the character of a continuous flow (Figs. 4.2a, 4.2b). Its depth is mostly shallow, but in places it reaches about 5 m. Visually, the

Fig. 4.2a Klátov Oxbow – surge Bödör (photo: F. Bottlik, 2016)

Fig. 4.2b Klátov Oxbow with coherent flow near Csótfa (photo: K. Benková, 2016)

water is clear, translucent. In Dunajský Klátov, the flow is conjoined from the right side by the connected Old Klátovský Channel and the Klátovský Channel, part of the water coming from springs in the area between Lehnice and Bellova Ves. In Topoľníky, the Klátov Oxbow takes the water from the Gabčíkovo – Topoľníky Channel and soon mouths in the form of a delta into the Little Danube (Michalko in Liščák et al., 2011).

The spring water is clear, characterized by relatively low temperatures in both canals (around 13 °C to 16 °C) and increased presence of heavy O and H isotopes. The chemical type of groundwater in the Klátov Oxbow, the Old Klátovský Channel and the Klátovský Channel is $Ca\text{-}HCO_3\text{-}SO_4$ with increased specific electrical conductivity (850 $\mu S.cm^{-1}$) compared to the water of the Little Danube (390 $\mu S.cm^{-1}$), which is of the chemical type $Ca\text{-}HCO_3$. The increase in the specific electrical conductivity value is also reflected in the increase in the content of NH_4, NO_3, Ca, Mg, Fe, Mn, Al, and Zn indicators, which exceeded the limit value pursuant to drinking water (Bottlik et al., 2013).

Isotopic composition of the Potônska mokraď Wetland groundwater ($\delta^{18}O$ = -9.55 to -10.46‰, $\delta^{2}H$ = -73.65 to -77.45‰) and Klátov Oxbow water ($\delta^{18}O$ = -9.17 to -10.74‰ , $\delta^{2}H$ = -71.81 to -79.40‰) is different from the isotopic composition of the Little Danube – Hrubý Šúr water ($\delta^{18}O$ = -10.60 to -12.20‰, $\delta^{2}H$ = -77.82 to -86.24‰) and documents the presence of waters that cross the Danubian Flat from the north (Vozokany – Jahodná area). Waters of similar chemical and isotopic composition have been documented in the Dudváh River north of the Little Danube (Michalko et al., 2015) and in groundwater at Vozokany in the HV-1 borehole, 15 m deep (Némethyová, 1980), isotopically also in piezometer in Jelka (Michalko et al. 2015).

The geological structure of the area in the area of the Little Danube in the Dolné Saliby – Dunajská Streda line is of such a character that the fluvial sediments of the Quaternary fill the palaeo-valley of the Váh River. Along this line, the thickness of the Quaternary sediments varies considerably, ranging from 80 – 100 m N of Tomášikovo, from 100 to 150 m S of Tomášikovo, from 80 to 100 m in Dunajský Klátov and 150 – 200 m to the south of Dunajský Klátov (Maglay et al., 2009). The sudden change in the thickness of the Quaternary sediments is probably due to vertical bedrock differentiation, which was covered by Neogene sediments with a lower coefficient of transmissivity value than of the Quaternary sediments. The differentiation of the Quaternary bedrock in this area causes that the Quaternary groundwater stream from Dolné Saliby rises up on the Neogene sediment barrier from 150 m to 80 m. This groundwater outlet from the Quaternary sediments has the character of a barrier spring and, depending on the shape of the spring, it can be characterized as a surface spring (10 km x 5 km).

The continuous increase in the coefficient of transmissivity of the Klátov Oxbow (especially in the area below the confluence with the connected Klátovský Channel) is caused by the increase of groundwater of the Danube origin, probably coming from the Little Danube (Michalko et al., 2015). The amount of water rising to the surface in the Klátov Oxbow (according to long-term observations of SHMI about 2,000 $l.s^{-1}$) quantifies it as one of the most significant natural groundwater outlets in Slovakia (Michalko et al., 2014a, Michalko et al., 2014b).

The Čiližská *mokraď Wetland* is located in a lane between the villages of Rohovce and Trávnik near the Danube River. The thickness of the Quaternary sediments increases from east to west from 20 m to 500 m (Maglay et al., 2007 in Malík, et al., 2007). The circulation and regime in this wetland is influenced by the flow rate in the Danube River and its channel system.

The *Okoličnianska mokraď Wetland* extends in the area approximately between Okoč, Kolárovo and Komárno, where the thickness of the Quaternary sediments increases from south to north from the value of 5 m near Komárno to 150 m near Okoč. The Neogene bedrock at the edge of the Danubian Flat is considerably vertically differentiated (Maglay et al., 2007 in Malík, et al., 2007). The circulation and regime in the Okoličnianska mokraď Wetland is influenced by the flow rates in the Danube, the Little Danube, the Váh and their channel systems.

In 1992, the *Gabčíkovo Waterworks* on the Danube River was put into operation, whose construction began in 1978. Its aim is to generate electricity through 8 Kaplan turbines (which generate 720 MW and produce approximately 2.2 billion MWh per year – approximately 8% of the total energy consumption in Slovakia), protection of the area from flooding, regulation of the level of the Danube and ensuring year-round navigability of the river as well as protection of the natural environment. The WW consists of several objects. These are mainly the Čunovo reservoir (area of 40 km^2), a 17 km long supply channel (between Čunovo reservoir and Gabčíkovo), the Gabčíkovo stage with power plant and two lock chambers, a 8.2 km outlet channel (between Gabčíkovo and Sap), inundation (dam) and flood control measures (modifications to existing dams, including metering systems, seepage and drainage channels, and the construction of pumping stations for pumping internal water to reduce water in the channel network).

From the long-term assessment of the groundwater regime trends, a decrease trend of the groundwater level on all groundwater observation objects was recorded until the WW was put into operation in the given area. The largest decreases prevailed in the upper part of the area of interest along the Danube – Petržalka, Podunajské Biskupice, Kalinkovo. Downstream, the decline in trends dropped, in the vicinity of Sap and Medveďov there were only slight decreases.

After the WW commissioning (in the observed period 1993 – 2002), the character of the trends was mostly changed to ascending (Fig.4.3). The water level increased in Bratislava (blue colour), in the upper part of Žitný ostrov up to Šamorín and towards the Little Danube. Decreases occurred from the beginning of the supply channel to the mouth of the outlet channel into the Danube, with the

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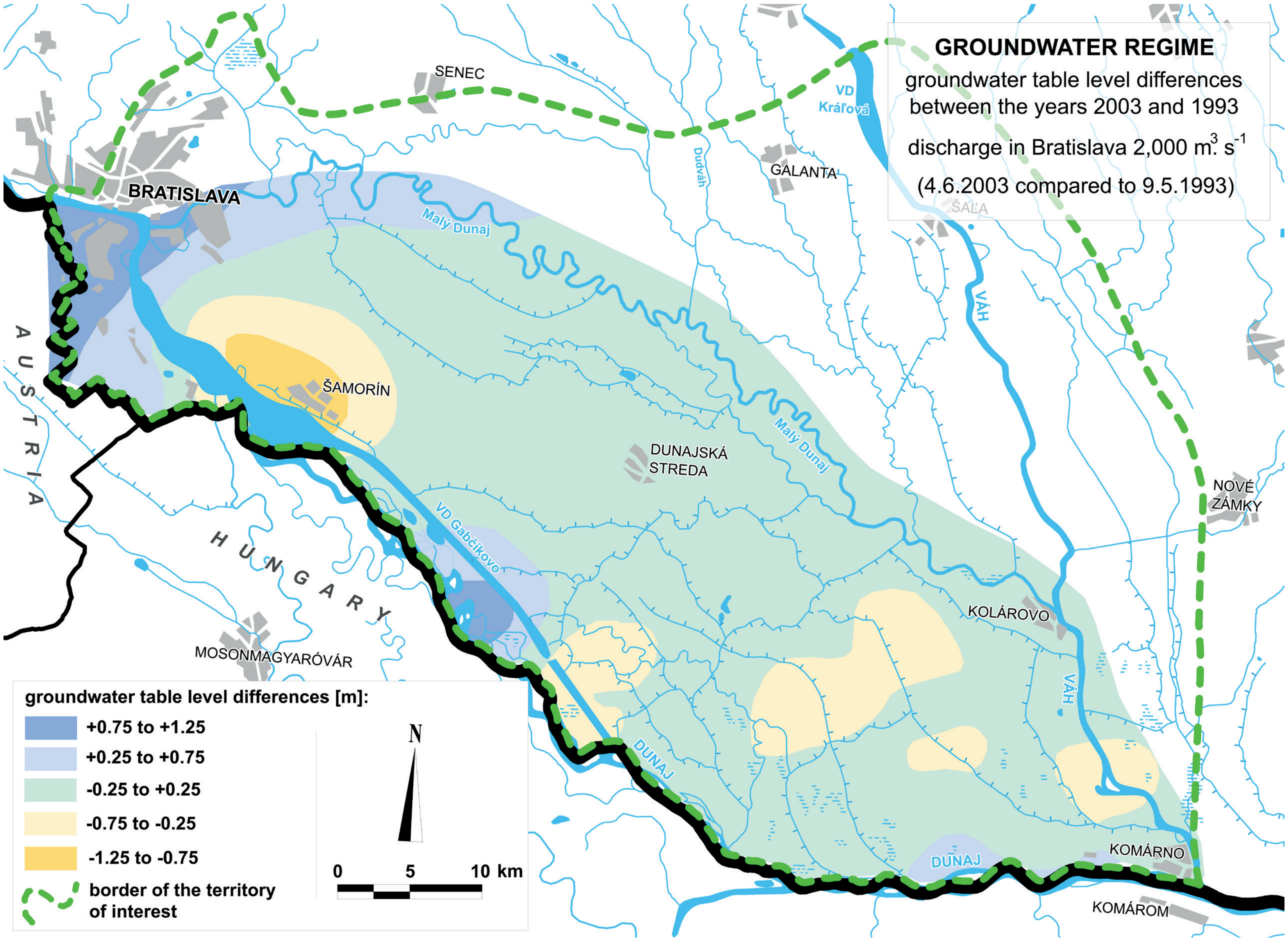

Fig. 4.3 Map of groundwater level differences between 1993 and 2003 (modified after Mucha et al., 2004)

largest decrease in Dobrohošť and Gabčíkovo – brown colour (Mucha et al., 2004).

The groundwater regime in the area of interest was evaluated in 1994 – 2003 in the right bank of the Danube in 2 profiles (AA´, BB´), in the area between the Danube and the Little Danube in 4 profiles (CC´, DD´, EE´, FF´) – Fig.

Tab.4.1 Average and extreme levels of groundwater level and fluctuations in longitudinal profiles of studied area in 1993 – 2002 according to SHMI data

Profile designation	Elevation (m a.s.l.)	H_{max} b.s. (m)	H_{min} b.s. (m)	H_{mean} b.s. (m)	Oscillation (m)
A-A´	136.25-132.88	2.39-6.59	2.74-6.93	2.55-6.76	0.33-0.35
B-B´	134.74-131.50	1.35-5.20	3.09-5.21	2.63-5.59	0.80-1.80
C-C´	122.98-114.94	0.52-2.63	3.09-4.26	2.57-3.73	1.20-3.70
D-D´	134.40-110.53	0.14-4.25	2.54-5.77	2.03-5.21	0.54-3.88
E-E´	131.39-108.67	0.83-3.56 (7.07 PB)	2.03-4.09 (7.52 PB)	1.52-3.85 (7.30 PB)	0.44-1.20
F-F´	134.23-108.80	0.67-6.28 (7.31 PB)	2.10-6.90 (7.92 PB)	1.70-6.60 (7.65 PB)	0.32-1.77

Legend: PB – Podunajské Biskupice

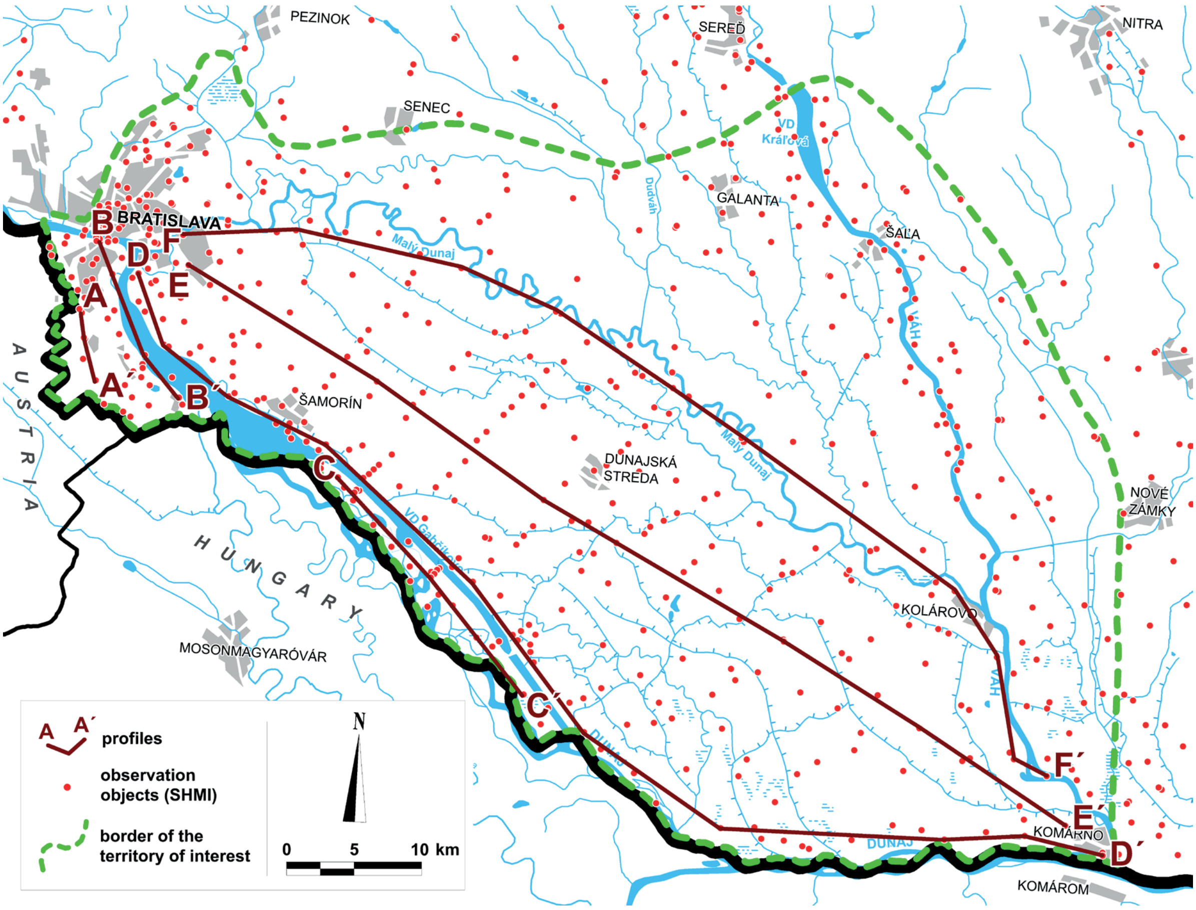

Fig. 4.4 Situation of longitudinal profiles in the area of interest – in the area of Žitný ostrov and the Danube right bank

4.4. The comparison of the mean values of groundwater level and oscillation range is shown in Tab. 4.1

Hydroisohypses (Fig. 4.5) were constructed on the basis of interpolation of the measured groundwater level levels in SHMI's observation objects. The respective terms for lower, average and higher levels were determined on the basis of a selection from the time series of November 1, 1995 – October 31, 2001.

From the large-scale sources from which the groundwater from the Quaternary aquifer is exploited, the water source (hereinafter WS) Jelka is located in the northern part of the territory. In the southern part of the territory – on the Žitný ostrov area there are WS Kalinkovo, Šamorín and Gabčíkovo and in the right bank of the Danube it is the water source Pečniansky les (Fig. 4.6) and Rusovce-Ostrovné Lúčky-Mokraď.

The WS Jelka from year 1969 consists of seven wells HJ-1 to HJ-7, which were realized to a depth of 44 – 65 m. An exploitable quantity of 500 $l.s^{-1}$ is approved for the water source in category A (Act 364/2004 Coll.). In 2012, from the 7 wells there were taken 399 $l.s^{-1}$.

In the WS Kalinkovo in year 1972 there were realized 10 wide-profile hydrogeological boreholes NVZ-1 to NVZ-10 to a depth of 55 – 80 m. An exploitable quantity of 660 $l.s^{-1}$ is approved for the water source in category A (Act 364/2004 Coll.). In 2012, there were taken only 48 $l.s^{-1}$ from 5 wells.

The WS Šamorín was built in years 1973 – 1981. It consists of 16 hydrogeological wells HGŠ-1 to HGŠ-16, which were built to a depth of 65 – 160 m. For the water source, the exploitable quantity in category A 600 $l.s^{-1}$ has been approved. Currently, 7 wells are being used yielding 233 $l.s^{-1}$.

The WS Gabčíkovo consists of 13 hydrogeological wells HAŠ-1 to HAŠ-13, which were realized in the period 1976 – 1984 to a depth of 85 – 90 m. An exploitable quantity of 3,000 $l.s^{-1}$ has been approved for the water source in category C_1. At present, 13 wells are used yielding 465 $l.s^{-1}$.

The WS Pečniansky les was built in the year 1976 in the right bank of the Danube. It consists of 34 wide-profile boreholes D-1 to D-34, which were realized to a depth of 10 – 13.5 m. An exploitable quantity of 350 $l.s^{-1}$ has been approved for the water source in category A. In y. 2012, the water was exploited from 17 wells yielding 174 $l.s^{-1}$.

The Rusovce-Ostrovné Lúčky-Mokraď consists of 23 wells ST-1 to ST-23, which were realized in yrs. 1978 – 1985 to a depth of 50 – 80 m. An exploitable amount of 1.828 $l.s^{-1}$ has been approved for the water source in category B. In year 2012, the water was exploited from 23 wells yielding 834 $l.s^{-1}$.

The groundwater of the Neogene sediments, which is characterized by a confined table level, is utilised from the level of about 80 – 412 m b.s. through hydrogeological wells in the northern and north-eastern part of the territory (Šaľa, Galanta, Nové Zámky, Trnovec nad Váhom, Vlčany and others) – Fig. 4.7.

4.6.2 Hydrogeochemical properties of groundwater of the Quaternary sediments

From the hydrogeochemical point of view, groundwater bound to the Quaternary aquifers can be characterized predominantly as fluviogenic with varying anthropogenic effects. Among the mineralization processes dominant are mainly hydrolysis of silicate minerals (the predominant material of the gravel-sand Quaternary sediments), dissolution of carbonates (usually present in the pebble material of gravel and loess) and oxidation of sulphides – mainly pyrite (a common accessory mineral of gravel).

As the chemical composition of groundwater in the region under consideration largely depends on the chemical composition of water in the Danube, the Tab. 4.2 shows basic statistical parameters of selected components (Bodiš 2005 in Benková et al., 2005).

<u>In the northern part of the Danubian Flat</u>, five chemical groundwater types were earmarked for the Quaternary. These are A_1 distinct type, Ca(Mg)-HCO_3 with an average TDS value of 746 $mg.l^{-1}$, A_2 indistinct type, Ca(Mg)-HCO_3 with an average TDS value of 940 $mg.l^{-1}$, intermediate and mixed type, predominantly components A_2 and S_2 (SO_4) with a TDS value of 173 $mg.l^{-1}$, a mixed type with a TDS value of 1,334 $mg.l^{-1}$ and hydrosilicatogenic water of the A_1 type, Na-HCO_3 with a mean TDS value 1,000 $mg.l^{-1}$.

In terms of groundwater quality classes (Tab. 4.3), there are represented classes A, B, D, F, H, with dominant class D. Groundwater of the highest class A is represented in the vicinity of Malý Jatov, the B class was verified in the wider surroundings of Jelka along the course of the Little Danube between Hrubý Šúr and Mostová and in the vicinity of Senec. In the territory of Bratislava and its close surroundings and in the area of Jelka-Komárno, groundwater is represented mainly by the quality class D. The deteriorated class F of the groundwater quality has been identified between Bratislava - Prievoz and Bernolákovo and between Kráľová pri Senci and Reca. The worst quality of the H-class was verified between Veľké Úľany and Hrubá Borša, then in the area of Vozokany, Saliby and Tešedíkovo, Jatov and Trnovec nad Váhom; in particular above-the-limit concentrations of ***chlorides, nitrates, sulphates and ammonium ions*** have been found (Bodiš, 2013 in Bottlik et al., 2013).

<u>In the southern part of the Danubian Flat</u> on the Žitný ostrov territory and on the right bank of the Danube, the chemical composition of groundwater due to the greater thickness of the Quaternary compared to the northern part of the Danubian Flat was characterized up to 25 m and at the level of 25 m. At the level up to 25 m, three chemical types of water were designated, namely A_2 distinct type, Ca-(Mg)-HCO_3 with an average TDS value of 462.3 $mg.l^{-1}$, A_2 indistinct type, distinct with an average TDS value of 661.8 $mg.l^{-1}$ and an intermediate and mixed type with a predominance of A_2 and S_2 (SO_4) components with an average TDS value of 911 $mg.l^{-1}$. The *first type* of groundwater is predominantly bound to the transversal zone of the Danube practically from Bratislava to Kližská Nemá. In the area below Trstená na Ostrove, the representation of this type extends below Dunajská Streda and Veľký Meder. It is represented locally between Kolárovo and Topoľníky and north of Tomášov. The first type is followed in the region by the *second type*, which is characteristic in a continuous lane from Bratislava to Kolárovo. The *third type* is bordered on the southern side by the line Podunajské Biskupice – Štvrtok na Ostrove – Horná Potôň – Malé Dvorníky – Veľký Meder – Zlatná na Ostrove – Komárno. From the northern side, this continuous lane is bounded by the flow of the Little Danube till Topoľníky and continues in the direction of Sokolce, Štúrovo to the Váh River.

At the level of 25 m, three chemical types of water were designated as A_2, Ca-(Mg)-HCO_3 type with an average TDS value of 380.6 $mg.l^{-1}$, intermediate and mixed type with predominance of A_2 a S_2(SO_4) components with an average TDS value of 680 $mg.l^{-1}$ and A_1, Na-HCO_3 type with an average TDS value of 625.9 $mg.l^{-1}$. At this level, the *first type* of groundwater is absolutely prevalent. This suggests some stabilization of the water-rock system without much anthropogenic agents. Locally, however, the values of TDS can reach 1,000 $mg.l^{-1}$. The *second type* of groundwater is bound to the Janíky – Oľdza area

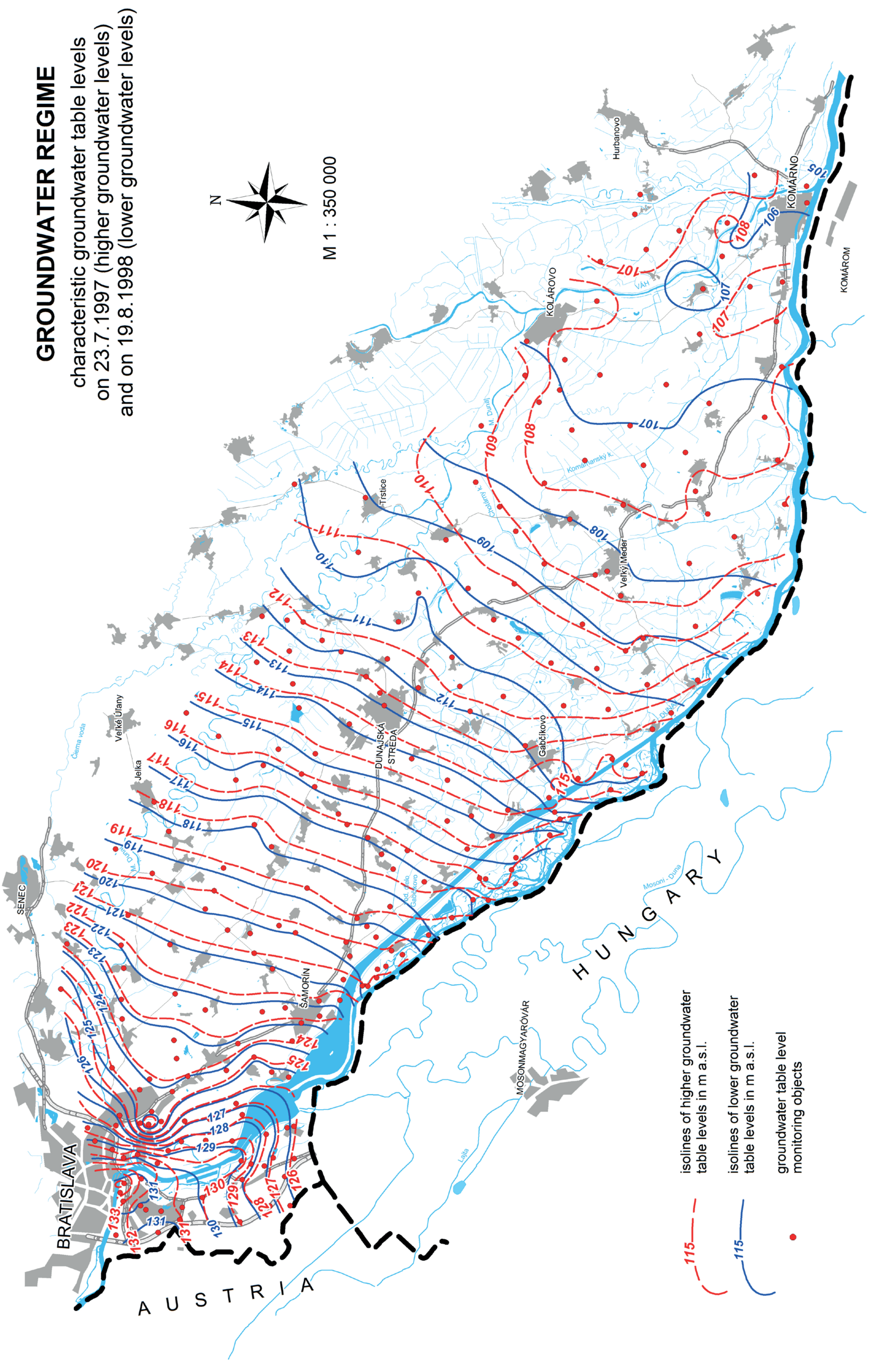

Fig. 4.5 Map of hydroisohypses at high and low water levels (Černák in Benková et al., 2005)

Fig. 4.6 Water source Pečniansky les (photo: K. Benková, 2018)

Fig. 4.7 Artesian well Šaľa-Veča (photo: F. Bottlik, 2013)

and can be justified as an upper reach. The *third type* of groundwater is located in the south-eastern part of Žitný ostrov (Kameničná – Veľký Lél – Komárno area).

At a *level of up to 25 m*, the A-class groundwater is characteristic mainly for the area of the narrower Danube zone from Bratislava to Vojka. Class B is typical for the central part of Žitný ostrov, i.e. from Bratislava till Dolný Štál. However, its homogeneity is interrupted by the cross-lane of deteriorated D-H water quality in the wider surroundings of Dunajská Streda due to the increased density of point sources of pollution (especially landfills) in this area and also the high degree of land use. For the Danube riparian zone from Vojka to Komárno and for the eastern part of Žitný ostrov, the D-class of groundwater quality is most represented. In this part is also represented the worst H class of quality in the area Kližská Nemá – Veľké Kosihy and also Zlatná na Ostrove – Komárno. Significantly deteriorated groundwater quality classes (F to H) occur in the area bounded from the southern part by the line Podunajské Biskupice – Štvrtok na Ostrove – Michal na Ostrove and from the northern part bounded by the Little Danube. In the eastern part of Žitný ostrov, the worst H quality class is represented in the transverse lane Topoľníky – Veľký Meder and locally in the area Bodza – Zemianska Oľča.

The *right bank of the Danube* is characterized by the D quality class from Petržalka to Rusovce in the narrower riparian zone and further towards Čunovo in the wider area of Rusovce-Ostrovné Lúčky-Mokraď water source. The area along the state border with Austria can be characterized as an area with deteriorated F class of groundwater quality with sources of contamination probably in Austria.

A completely different qualitative picture of groundwater is at a level of 25 m. The groundwater quality at this level is significantly better than at the higher level.

Tab. 4.2 Basic statistical parameters of selected indicators of surface water of the Danube

	years 1992 – 2001					
	min.	**max.**	**mean**	**STD**	**variance**	**number**
Ca	36.07	86.40	59.53	8.71	75.97	163
Cl	0.00	35.00	18.64	5.57	31.7	166
Fe	0.023	2.470	0.34	0.37	0.139	139
HCO_3	134.00	274.00	192.77	22.90	524.79	168
Mg	10.10	26.75	14.11	2.60	6.78	165
Mn	0.002	0.180	0.033	0.031	0.001	139
Na	4.40	42.20	9.98	3.80	14.43	166
NH_4	0.025	3.37	0.273	0.284	0.081	169
NO_3	1.40	17.50	10.28	3.25	10.61	169
O_2	7.200	15.20	10.47	1.78	3.17	171
SO_4	18.00	42.30	29.18	5.72	32.73	169
Conductivity	232	518	384	61	3,731	169

Note: all the values are in mg.l^{-1}, conductivity in μS.cm^{-1}

Tab. 4.3 Groundwater quality classification scheme

GROUNDWATER QUALITY CLASS

Class label	Class quality characterisation 1	2	3
A	+	+	+
B	+	+	–
C	+	-	+
D	+	-	-
E	-	+	+
F	-	+	-
G	-	-	+
H	-	-	-

\+ *complies with the earmarked*
\- *does not comply with the limit values set aside limit values*

ASSESSED INDICATORS AND THEIR LIMIT VALUES

Assessed indicators groups	Assessed indicators	Symbol	Unit	Limit values
1	**Aluminium**	Al	$mg.l^{-1}$	0.2
1	**Arsenic**	As	$mg.l^{-1}$	0.01
1	***Barium***	*Ba*	*$mg.l^{-1}$*	*1*
1	**Cadmium**	Cd	$mg.l^{-1}$	0.003
1	**Chromium**	Cr	$mg.l^{-1}$	0.05
1	**Copper**	Cu	$mg.l^{-1}$	0.1
1	**Mercury**	Hg	$mg.l^{-1}$	0.001
1	**Ammonium ions**	NH_4	$mg.l^{-1}$	0.5
1	**Nitrites**	NO_2	$mg.l^{-1}$	0.1
1	**Nitrates**	NO_3	$mg.l^{-1}$	50
1	**Nickel**	Ni	$mg.l^{-1}$	0.02
1	**Antimony**	Sb	$mg.l^{-1}$	0.005
1	**Lead**	Pb	$mg.l^{-1}$	0.01
1	**Selenium**	Se	$mg.l^{-1}$	0.01
2	**Chlorides**	Cl	$mg.l^{-1}$	100
2	**Fluorides**	F	$mg.l^{-1}$	1.5
2	**Iron**	Fe	$mg.l^{-1}$	0.2
2	**Manganese**	Mn	$mg.l^{-1}$	0,05
2	***Phosphates***	*PO_4*	*$mg.l^{-1}$*	*1*
2	**Sulphates**	SO_4	$mg.l^{-1}$	250
2	**Zinc**	Zn	$mg.l^{-1}$	3
3	**Calcium and magnesium (Ca + Mg)**	Ca + Mg	$mmol.l^{-1}$	1.1 až 5
3	**Chemical oxygen demand**	$CHSK_{Mn}$	$mg.l^{-1}$	3
3	**Magnesium**	Mg	$mg.l^{-1}$	125
3	**Water saturation with oxygen**	O_2	%	>50
3	**Water reaction**	pH		6.5 to 8.5
3	***TDS***	*RL*	*$mg.l^{-1}$*	*1,000*

The elements in italics are not mentioned in the decree of the MH SR no. 151/2004 Coll. on requirements for drinking water and drinking water quality control

Mainly A and C quality classes dominate, while E, F and G are not represented at all. G and H classes, which appear at the higher level of the aquifer in the northern part of Žitný ostrov, are manifested only by point anomalies of classes G and H. The situation in Zemianska Olľča, Veľké Kosihy and Komárno is relatively more complicated, where the quality classes D, F, G and H are intermittently interchanged. The worst H water quality class is located only in the area of Kolárovo and Bodzianske Lúky, which is bounded by a zone with D quality class and locally east of Kostolné Kračany.

The area *of the Danube right bank* falls at the described level ***below 25 m within the A-class*** (Bodiš, 2005 in Benková et al., 2005).

In the marginal parts, local precipitation, local watercourses and Váh water should be considered as a source of groundwater. However, the Danube water plays a decisive role, either directly or indirectly through the oxbows and channels network. The isotopic composition of oxygen $\delta^{18}O$ of monthly accumulated precipitation fluctuated in the centre of the area of interest in the precipitation station Topoľníky in the period 1989 – 1998 in the interval -7.12 to -14.4‰ (the average value was -9.43‰). At the W border of the territory under study the average value of $\delta^{18}O$ = – 8.98‰ (at the station Bratislava – Koliba) and in E outskirts (in station Mochovce) -9.11‰ (Kantor et al., 1989; Michalko 1998).

The *surface water of rivers and reservoirs* originates either from local rainfall (and shorter local rivers and streams) or from rainfall from the higher altitudes of the Western Carpathians, which larger rivers (e.g. Váh) have or had brought to the area in the geological past. Their isotopic composition also corresponds to this situation.

Isotopic composition of water ine the *Váh River* in Vlčany during the period of 2013 – 2014 (12 samples) showed mean values $\delta^{18}O$ = -10,42‰, $\delta^{2}H$ = -73,87‰, *Čierna voda River* in Čierna Voda $\delta^{18}O$ = -10.56‰ and $\delta^{2}H$ = -77.51‰ and *Dudváh River* in Čierny Brod $\delta^{18}O$ = -9.47‰ and $\delta^{2}H$ = -69.10‰ (Michalko et al., 2015).

A significant amount of surface water flows into the Danube Lowland from the Alps by the Danube River. This isotopically light water (diametrically different from that of other sources) dominate the oxbows and practically also channel system, it is also present in most gravel pits (Kantor et al., 1987, 1989). The isotopic composition of the Danube in Bratislava monitored in the period 1982 – 1997 with a monthly step (346 samples) fluctuated ($\delta^{18}O$) in the interval -13.53 to -10.31‰ with an average value of $\delta^{18}O$ = -11.31‰ (Kantor et al., 1987; 1989; Michalko et al., 1997; Michalko et al., 2014a; Bodiš et al., 2015). During renewed monitoring since y. 2010 $\delta^{18}O$ = -11.23‰ and $\delta^{2}H$ = -80‰ average values were reached (Michalko et al., 2014a; Michalko et al., 2015).

The isotopic composition of the *Little Danube* follows the mother river with little influence of heavier water from the left tributaries. The average isotope values of oxygen and hydrogen in the surface water of the Little Danube in Jahodná in the period 2013 – 2014 were $\delta^{18}O$ = -11.05‰ a $\delta^{2}H$ = -80.90‰ (Michalko et al., 2015).

In the Quaternary sediments of the Danubian Plain, water of Alpine origin, which originates from the bank infiltration of the Danube, or from the streams of the river oxbow and channel system, is predominantly present. It can also be distinguished from local waters by its isotopic composition (Kantor et al., 1985; 1987; 1989; Ďurkovičová et al., 1993; Michalko et al., 1997; Michalko, 1998). The significant annual minimum of $\delta^{18}O$ in the Danube caused by snow melting at higher altitudes in the Alps is characterized by a value on 1.0 – 1.5‰ lower than the average value. The flow situation is accompanied by high flow, reduced conductivity and water temperature. Since the minimum lasts relatively shortly, this marker for bank infiltration can be tracked to a distance of several kilometres to get an idea of the flow rate. Rodák et al. (1995) in the area of Kalinkovo estimated the rate of infiltration in the preferred zone up to 2 km per year. Thereafter, the annual changes are wiped out, but the groundwater retains light "Danube" average values ($\delta^{18}O$ -10.5 to -11.0‰).

Tab. 4.4 Selected parameters of hydrogeologic units of the Danubian Flat

Hydrogeologic unit	Hydrogeologic sub-unit	Collector	Number of wells	T ($m^2.s^{-1}$)	k ($m.s^{-1}$)	TDS ($g.l^{-1}$)	Dominant chemical type of water
Crystalline	Palaeozoic of Pezinok Carpathians	granitoids	37*	$4.3.10^{-5}$	$4.8.10^{-6}$	0.17 – 0.41 (mean 0.25)	A_2 indistinct $Ca\text{-}Mg\text{-}HCO_3$
Mesozoic	Late Triassic– Jurassic of Transdanubian Mts. – GTW	limestones, dolomites, dolomitic limestones	3	$1.35.10^{-4}$		2.2 – 3.1	Mixed type with prevalent $Ca\text{-}SO_4$ with elevated Na-Cl content
Neogene volcanics	Early Badenian (Langhian) Šurany volcanics – GTW	andesites	1	$1.1.10^{-5}$	$4.9.10^{-7}$	17 – 23	fossil marine water of the type Na-Cl (SO_4)
Sedimentary Neogene below 500 m	Pannonian, (Tortonian), Pliocene of the Danubian Flat – GTW	sands, sandstones	33	$5.3.10^{-4}$	$6.7.10^{-6}$	0.5 – 8.3	$Na\text{-}HCO_3$ and $Na\text{-}HCO_3\text{-}Cl$
Sedimentary Neogene to 500 m	Pannonian (Tortonian), Pliocene, N part of the Danubian Flat	sands, sandstones	46	$6.08.10^{-4}$	$3.64.10^{-5}$	0.3 – 1.06 (mean 0.53)	A_2 distinct, with depth transition from $Ca\text{-}(Mg)\text{-}HCO_3$ to $Na\text{-}HCO_3$
	Pliocene, N part of the Danubian Flat	sands, sands with gravel	128	$1.55.10^{-3}$	$9.84.10^{-5}$		
	Pliocene, S part of the Danubian Flat	sands, sands with gravel	55	$1.84.10^{-3}$	$1.09.10^{-4}$		
Quaternary	Fluvial, N part of the Danubian Flat – bottom accumulation	sandy gravels, gravels, sands	492	$1.55.10^{-2}$	$2.5.10^{-3}$	0.27 – 0.76 (mostly 0.4 – 0.6) at anthropogenic impact above 0.8	A_2 distinct, $Ca\text{-}Mg\text{-}HCO_3$
	Fluvial, N part of the Danubian Flat – middle terraces	sandy gravels, gravels	19	$1.10.10^{-3}$	$6.0.10^{-4}$		
	Proluvial, N part of the Danubian Flat	loamy, sandy-loamy gravels	5	$8.49.10^{-4}$	$3.0.10^{-4}$		
	Fluvial of the right bank of the Danube	sandy gravels, gravels, sands	110	$5.03.10^{-2}$	$5.90.10^{-3}$		
	Fluvial of the upper part of ŽO	sandy gravels, gravels, sands	98	$3.38.10^{-2}$	$4.31.10^{-3}$		
	Fluvial of the central part of ŽO	sandy gravels, gravels, sands	406	$4.50.10^{-2}$	$3.71.10^{-3}$		
	Fluvial of the lower part of ŽO	sandy gravels, gravels, sands	198	$6.85.10^{-3}$	$8.61.10^{-4}$		

*Note: * – wells out of the territory of the Danubian Flat, GTW – geothermal water, ŽO – Žitný ostrov*

The isotopic composition of the groundwater of the Danubian Flat Quaternary has been monitored since the early 1980s (Kantor et al., 1985); the spatial isotope data are at hand since1988 (Kantor et al., 1989), monitoring of $\delta^{18}O$ in the piezometers network had been part of monitoring the impact of the WW Gabčíkovo until 1996. Virtually all groundwater in the Quaternary sediments of Žitný ostrov and the Danube right bank must be derived from the Danube. Ďurkovičová et al. (1993), Michalko et al. (1997), in relation to the isotopic composition of groundwater, delineate the area adjacent to the Danube with a rapid impact of the watercourse, the area with the Danube homogenized waters practically throughout the Žitný ostrov area and the area affected by water from local precipitation near the Little Danube (Jelka, Jánovce, Jahodná) and in piezometer Oľdza. Isotopically heavy water is also present in the piezometer Jarovce on the right bank of the Danube.

At present, isotopically lighter water (unambiguously of the Danube affiliation) occurs in the entire depth of the profile at least till the Oľdza – Dunajská Streda line. The exception is the upper horizon (level 5 – 8 m) of the aquifer verified in a piezometer in Veľký Blahov (SHMI, Final report 7293), where isotopically heavier water is present, probably altered due to evaporation (Michalko et al., 2014a; 2014b; 2015). The influence of irrigation water (Ženišová et al., 2015) can be excluded due to climatic conditions.

4.7 Conclusions

Hydrogeological units earmarked in the Danubian Flat are represented by important regional groundwater aquifers, whose overview and selected parameters are documented in Tab. 4.4. On the basis of the average value of the coefficient of transmissivity of aquifers with *fissure permeability*, it is possible to observe its increase from andesites and granitoids to carbonates. For aquifers with *intergranular permeability*, the value of the coefficient of transmissivity increases from the sands and sandstones of the Pannonian (Tortonian) to the sands of Zanclean. ***The most permeable are the fluvial sediments of the right bank of the Danube and the central part of Žitný ostrov***, as well as the fluvial sediments of the upper part of Žitný ostrov and the northern part of the Danubian Flat. The coefficient of transmissivity of the fluvial sediments of the lower part of Žitný ostrov is almost one order lower compared to the right bank of the Danube.

The TDS of groundwater of the Quaternary and shallow Neogene aquifers is not very different and reaches values mostly in the interval of approx. 0.3 – 1.0 $g.l^{-1}$.

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