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Estimation of the natural groundwater recharge using tritium-peak and tritium/helium-3 dating techniques in Hungary

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Quantification of natural groundwater recharge in three study sites within the Great Hungarian Plain was performed using environmental tracer techniques, based on utilization of tritium and helium-3 isotopes in groundwater samples taken from multilevel well-nests. Transport models were calibrated by the measured ^{3}H activities at different depths below surface. The 1963 tritium bomb-peak was used to determine the average natural groundwater recharge. Rates of 48 ± 6 mm/yr, 62 ± 8 mm/yr and 27 ± 3 mm/yr, respectively were obtained. The ^{3}H/^{3}He dating technique was also used to determine age profiles at the three sites, giving recharge rates of 48 ± 6 mm/yr, 63 ± 9 mm/yr and 22 ± 4 mm/yr respectively. Although the recharge rates calculated by the two methods agree well with each other, these two approaches to recovering recharge rates are based on different recharge properties. Modelling of the bomb peak distribution is mainly affected by the position of the bomb peak, hence the recharge rate obtained is not necessarily reliable for recent decades. In contrast, the ^{3}H/^{3}He age-depth profile averages the last 4–5 decades, and therefore may provide a better estimation of long term recharge. A third approach to calculating recharge rates using a simple soil moisture—stable isotope approach was found to only be reliable over the most recent few years.

Keywords: groundwater recharge, tritium-peak method, ^{3}H/^{3}He dating, Great Hungarian Plain, transport modelling

Introduction

Groundwater is a strategic and national security topic for Hungary; it is important to understand the natural groundwater recharge conditions in order to establish new and sustainable groundwater management (Eross *et al*., 2012; Szocs *et al*., 2013; Székely *et al*., 2015; Madarász *et al*., 2015).

Environmental tracers have been widely used in isotope hydrology (Cook and Herczeg, 2012). One of the first tracers was tritium (^{3}H) derived from atmospheric nuclear weapon tests. At many sites the so-called bomb peak can still be identified in recharge areas, being an ideal time marker of the early 60's (Massmann *et al*., 2009; Cartwright and Morgenstern, 2012). Additionally, in isotope hydrology, apparent ages are estimated with ^{3}H/^{3}He (Kaown *et al*., 2009; Visser *et al*., 2013), ^{85}Kr (Momoshima *et al*., 2009; Delbart *et al*., 2014), CFCs (Gourcy *et al*., 2009; Han *et al*., 2012), SF_6 (von Rohden *et al*., 2010; Darling *et al*., 2012), SF_5CF_3 (Busenberg and Plummer, 2008; Beyer *et al*., 2014).

Based on previous studies in Hungary the average groundwater recharge is 50 to 100 mm/yr on sandy soils in the Great Hungarian Plain, while much higher values between 150 and 200 mm/yr have been determined in karstic regions using tritium-based techniques (Groundwaters in Hungary, Ministry for Environment and Water, Guide, 2006). Other studies provided 60 mm/yr and 82 mm/yr average recharge rates based on steady-state water balance models and numerical flow models in the Nyírség area during the period 1961–1990 (Ács and Simonffy, 2012).

In this study, our approach has been the application of the two environmental tracers tritium and ^{3}H/^{3}He to determine the apparent ages of water. In December 1998 well nests were constructed at Méntelek and Fischerbócsa, allowing tritium-depth profiles to be measured based on samples from six and 11 different depths respectively. The simple tritium-peak method was applied by Deák after the 1998 field measurements to estimate the average groundwater recharge at the two investigated test sites on the Danube-Tisza Ridge (Deák, 2006). The first rough

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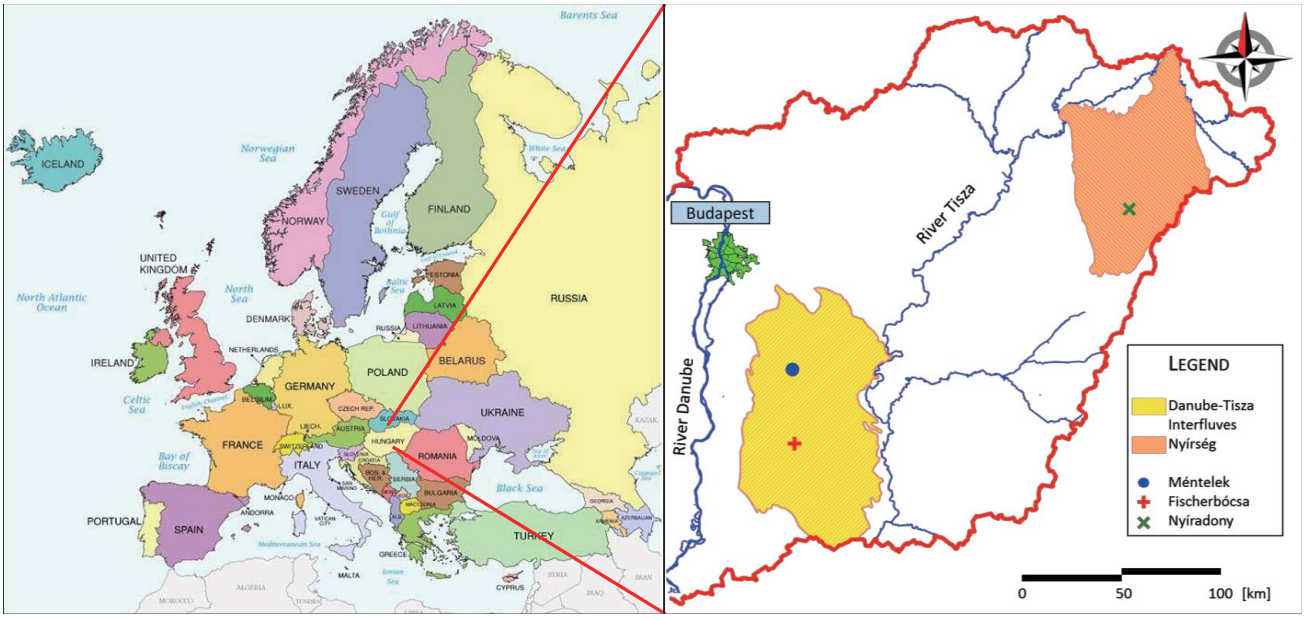

Fig. 1. The location of the research sites (marked with the symbols on the right-hand figure).

analytical calculation gave 57 and 75 mm/yr recharge rates, respectively (the calculations run in the period 1963–1998) (Deák, 2006; Szucs *et al.*, 2015).

The aim of the present study was to investigate the natural groundwater recharge to the saturated zone through sandy soils on regional recharge areas in Hungary within the Carpathian Basin, using isotope hydrological tools and transport modelling. The selected research sites of Méntelek and Fischerbócsa are located on the Danube-Tisza Ridge (in the Danube-Tisza Interfluves), central Hungary, while a third site is located at Nyíradony in the Nyírség area, East Hungary (Fig. 1). All three sites are situated on typical porous recharge areas built up by alluvial sand with nearly vertical groundwater flow (Erdélyi, 1976; Deák, 2002; Juhász, 2002), which is why areas were selected for the establishment of research sites. At each site, well nests screened at different depths were used.

Study Area

All of the study sites are situated in the Great Hungarian Plain. The areas are on the two major recharge territories of the Great Hungarian Plain. The Danube-Tisza Interfluve is located between the Danube and Tisza rivers with an approximately 10,000 km^2 area at an elevation of 100–130 m above Baltic Sea level. The area is a flatland with variable surface topography, mostly sand dunes. The central, relatively higher area between the two rivers has a N-S orientation and is referred to as the Danube-Tisza Interfluve, where two out of the three study sites are located. The sediments originate from the alluvium of the palaeo-Danube rather than from current river deposition. Aeolian sand hills are also typical for the region, with numerous local discharge zones between them. The thickness of the sand layer is 30–120 m, which determines significantly the hydrogeological conditions of this region. At a local scale precipitation is the only source of the natural groundwater recharge. Average annual rainfall is 599 mm/yr, and annual average temperature is 10.9°C (Hungarian Meteorological Service).

The other research area is the Nyírség, which at 5100 km^2 is comparable in area to the Danube-Tisza Interfluve. The bedrock is a thick Quaternary-Miocene sediment sequence built up of fluvial and lacustrine sediments. At present the sand hills exceed a height of 150 m, while the plains average 100–110 m above Baltic Sea level. The area is characterized by sandy loess and loess sand (Rónai, 1985). The average depth of the water table fluctuates over time between 3–6 m below surface depending on the amount of the precipitation. Based on the natural-state pressure conditions the Nyírség is a regional recharge area (Virág, 2013).

The climate of the Nyírség is somewhat different compared to the typical climate of the Great Hungarian Plain. The winters are colder, the summers are cooler and the annual temperature fluctuations are not significant, due to the proximity of the Carpathian uplands. The Nyírség is characterized by greater rainfall than the rest of the Great Hungarian Plain. At 590 mm/yr, the annual rainfall is slightly lower than for the Danube-Tisza Interfluves, and the annual average temperature is also lower (10.0°C)

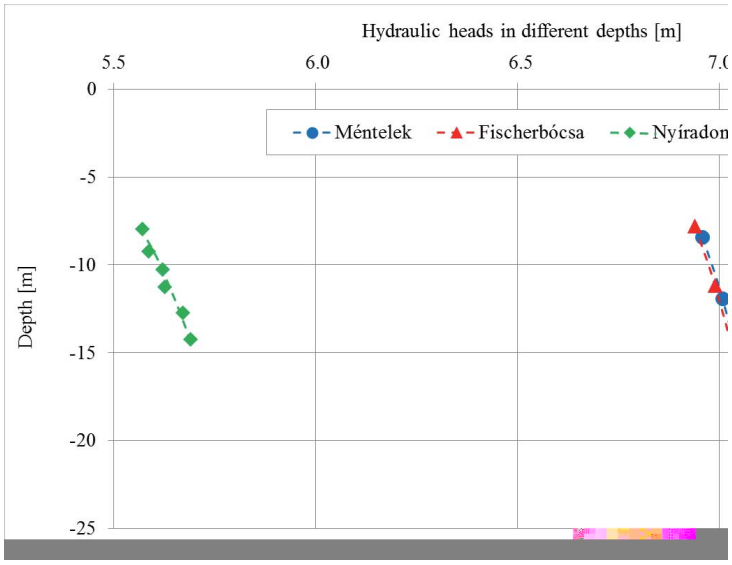

Fig. 2. The hydraulic heads (i.e., measured water levels below ground surface) vs. screen depth for the wells at each research site. These profiles indicate that water pressure is decreasing with increasing depth, showing the site is a recharge area.

(Hungarian Meteorological Service).

The hydraulic conditions of both the Danube-Tisza Ridge and the Nyírség contribute to the development of a classical regional groundwater flow system (Tóth, 1963). Water pressure (i.e., water level) vs. elevation profile is the only method in hydrodynamic analyses, which helpful in the examination of the vertical component of fluid flow directions by comparing the vertical pressure gradient to the ideal hydrostatic condition. Such investigations were applied in our research, the profiles in Fig. 2 clearly showing the hydraulic pattern indicating that the monitoring wells are located on recharge sites.

Applied Methods

Tritium-peak method and $^3H/^3He$ dating technique

Tritium (^3H), the radioactive isotope of hydrogen with a 12.32 year half-life, is a powerful tool in tracing groundwater flow paths. This environmental isotope as a natural tracer is used to describe circulation patterns in hydrology, hydrogeology and limnology research. In the 1960's the ^3H concentration strongly increased in the atmosphere due to thermonuclear weapon testing. Identifying the position of the 1960s bomb-peak in the groundwater using multilevel wells is the basis of the first part of the investigation. As an input the ^3H activity of precipitation from Vienna has been used because of its long record and territorial proximity to Hungary. The ^3H concentration of Vienna precipitation exceeded 3000 TU in 1963, and since then has decreased continuously. Nowadays, the background concentration is close to the natural level, fluctuating in the range 6–16 TU (IAEA WISER database for Vienna).

The $^3H/^3He$ ratio is an effective technique for dating young groundwater (Schlosser *et al.*, 1988; Stute *et al.*, 1997, 2007; Solomon *et al.*, 1993; Shapiro *et al.*, 1999; Visser *et al.*, 2007). The technique is based on the radioactive decay of ^3H and the accumulation of the ^3He decay product in groundwater. $^3H/^3He$ apparent ages provide direct travel times and can be applied to a single sample, whereas ^3H alone requires a depth profile to locate the ^3H-bomb peak. Groundwater flow velocities were determined from ^3H and ^3He samples collected from each of the three research sites at the Hertelendi Laboratory of Environmental Studies, Institute for Nuclear Researches, Hungarian Academy of Sciences, Debrecen, Hungary (Palcsu *et al.*, 2010; Papp *et al.*, 2012).

Numerical flow and transport modelling

Flow and transport modelling was based on finite-difference solutions of the saturated water flow and advection-dispersion equations. Since continuously measured groundwater levels do not exist from the past, we built steady-state models, which run from 1950 to the sample date (2010 and 2014, 2014 and 2015 in case of Méntelek, Fischerbócsa and Nyíradony respectively). A 1D flow and transport modelling procedure was applied to determine the vertical flow at each research sites. Besides the flow models, transport models were also created to investigate the tritium profile. The tritium concentration of the recharging water was defined as the input parameter through a time-variable boundary condi-

Table 1. Information about the research sites and the measured ^{3}H concentrations

Name of sampling position	Longitude	Latitude	Altitude [m]	Top of the screen [m]	Bottom of the screen [m]	Mean screening depth [m]	Date of sampling	Groundwater level [m]	^{3}H [TU]
Méntelek-soil-1	19°32′45″	46°57′53″	123.35			–6.25	05.12.1998		13.8 ± 1.4
Méntelek-soil-2	19°32′45″	46°57′53″	123.35			–7.75	05.12.1998		14.8 ± 1.5
Méntelek-soil-3	19°32′45″	46°57′53″	123.35			–9.25	05.12.1998		19.1 ± 1.9
Méntelek-soil-4	19°32′45″	46°57′53″	123.35			–10.25	05.12.1998		22.5 ± 2.3
Méntelek-soil-5	19°32′45″	46°57′53″	123.35			–11.25	05.12.1998		45.3 ± 4.5
Méntelek-soil-6	19°32′45″	46°57′53″	123.35			–12.00	05.12.1998		48.5 ± 4.9
Méntelek-soil-7	19°32′45″	46°57′53″	123.35			–12.25	05.12.1998		54.7 ± 5.5
Méntelek-soil-8	19°32′45″	46°57′53″	123.35			–13.25	05.12.1998		49.3 ± 4.9
Méntelek-soil-9	19°32′45″	46°57′53″	123.35			–14.75	05.12.1998		14.0 ± 1.4
Méntelek-soil-10	19°32′45″	46°57′53″	123.35			–16.35	05.12.1998		1.2 ± 0.1
Méntelek-soil-11	19°32′45″	46°57′53″	123.35			–22.10	05.12.1998		0.0 ± 0.5
Méntelek-well-1	19°32′45″	46°57′53″	123.35	–7.93	–8.93	–8.43	15.12.2010	–6.96	5.60 ± 0.16
Méntelek-well-2	19°32′45″	46°57′53″	123.35	–11.45	–12.45	–11.95	15.12.2010	–7.01	5.62 ± 0.20
Méntelek-well-3	19°32′45″	46°57′53″	123.35	–15.85	–17.85	–16.85	15.12.2010	–7.06	15.04 ± 0.43
Méntelek-well-4	19°32′45″	46°57′53″	123.35	–21.14	–23.14	–22.14	15.12.2010	–7.09	4.53 ± 0.14
Méntelek-well-1	19°32′45″	46°57′53″	123.35	–7.93	–8.93	–8.43	22.05.2014	–8.35	4.98 ± 0.14
Méntelek-well-2	19°32′45″	46°57′53″	123.35	–11.45	–12.45	–11.95	22.05.2014	–8.37	4.24 ± 0.12
Méntelek-well-3	19°32′45″	46°57′53″	123.35	–15.85	–17.85	–16.85	22.05.2014	–8.38	12.63 ± 0.33
Méntelek-well-4	19°32′45″	46°57′53″	123.35	–21.14	–23.14	–22.14	22.05.2014	–8.39	3.73 ± 0.07
Fischerbócsa-soil-1	19°33′31″	46°37′16″	116.66			–7.00	05.12.1998		10.8 ± 1.1
Fischerbócsa-soil-2	19°33′31″	46°37′16″	116.66			–12.00	05.12.1998		20.5 ± 2.1
Fischerbócsa-soil-3	19°33′31″	46°37′16″	116.66			–13.00	05.12.1998		24.0 ± 2.4
Fischerbócsa-soil-4	19°33′31″	46°37′16″	116.66			–14.00	05.12.1998		28.4 ± 2.8
Fischerbócsa-soil-5	19°33′31″	46°37′16″	116.66			–15.00	05.12.1998		28.6 ± 2.9
Fischerbócsa-soil-6	19°33′31″	46°37′16″	116.66			–23.00	05.12.1998		1.9 ± 0.2
Fischerbócsa-well-1	19°33′31″	46°37′16″	116.66	–7.30	–8.30	–7.80	22.05.2014	–6.94	4.83 ± 0.17
Fischerbócsa-well-2	19°33′31″	46°37′16″	116.66	–10.67	–11.67	–11.17	22.05.2014	–6.99	4.35 ± 0.16
Fischerbócsa-well-3	19°33′31″	46°37′16″	116.66	–14.87	–16.87	–15.87	22.05.2014	–7.04	4.75 ± 0.24
Fischerbócsa-well-4	19°33′31″	46°37′16″	116.66	–20.71	–22.71	–21.71	22.05.2014	–7.05	4.520.15
Nyíradony-well-1	21°52′11″	47°40′45″	151.52	–7.70	–8.20	–7.95	13.03.2014	–5.57	5.8 ± 0.4
Nyíradony-well-2	21°52′11″	47°40′45″	151.52	–9.00	–9.50	–9.25	13.03.2014	–5.59	4.8 ± 0.4
Nyíradony-well-3	21°52′11″	47°40′45″	151.52	–10.00	–10.50	–10.25	13.03.2014	–5.62	4.0 ± 0.3
Nyíradony-well-4	21°52′11″	47°40′45″	151.52	–11.00	–11.50	–11.25	13.03.2014	–5.63	4.1 ± 0.4
Nyíradony-well-5	21°52′11″	47°40′45″	151.52	–12.50	–13.00	–12.75	13.03.2014	–5.67	7.6 ± 0.5
Nyíradony-well-6	21°52′11″	47°40′45″	151.52	–14.00	–14.50	–14.25	13.03.2014	–5.69	18.8 ± 0.6

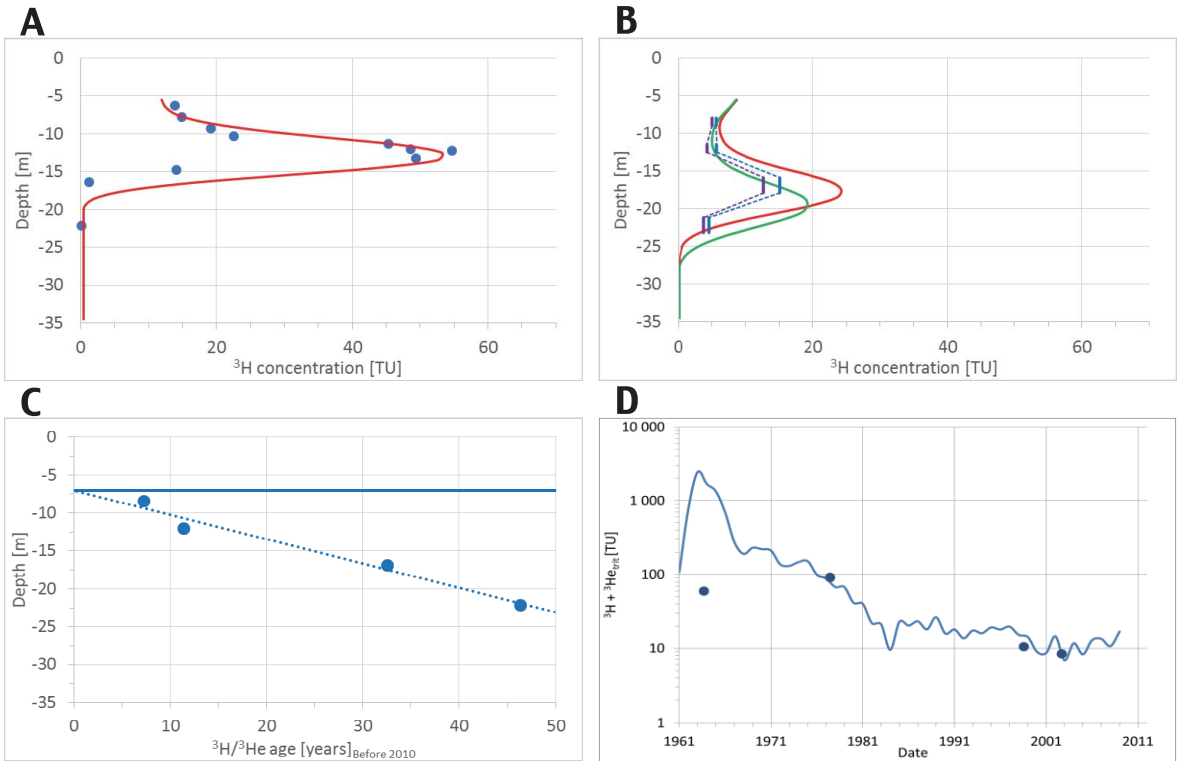

Fig. 3. Results for the Méntelek recharge area: A: tritium depth profile obtained from soil moisture in 1998, the dots represent measured values, while the solid line is from the model calculation; B: tritium concentrations of the well nest in 2010 and 2014, the vertical lines bound by dashed lines represent measured values for the whole screened depth, while the solid lines are from the model calculation; C: $^3H/^3He$ apparent ages vs. depth: the dots represent calculated age values, while the dashed and solid lines represent the linear age profile and water table, respectively; D: $^3H_{initial}$ as $^3H_{measured}+^3He_{tritiogenic}$ (circles) plotted onto the bomb peak curve (solid line).

tion. The recharge rates during the study periods were given as the input through time variable boundary condition (upper boundary conditions), while constant heads as a lower boundary conditions were applied. Based on the trial-and-error method, the modelled tritium profiles were compared to the measured tritium values, until the difference of the two profiles reached a minimum. In the models, the most sensitive soil hydraulic and transport parameters are the porosity and the dispersivity, but the calculated recharge rates depend strongly on the porosity of the soil.

Results and Discussion

Flow and transport models were created covering the 65-year-long time period between 1951 and 2015. We applied recharge driven boundary conditions for the flow modelling, and flux time-variant boundary conditions for the transport modelling. Field and laboratory tests were applied to identify the modeled sediments, and to investigate the hydraulic conductivity and effective porosity values. We defined continuous, homogeneous fine sand layers for each sites after the drilling logs, the geophysical soundings and the grain size distribution tests. Based on laboratory tests, the effective porosity values are 0.15, 0.15 and 0.13 in case of Méntelek, Fischerbócsa and Nyíradony, respectively. We assumed a 10% relative uncertainty for the porosity values.

The GNIP data for Vienna (https://nucleus.iaea.org/wiser/gnip.php) was taken as the basis for the tritium time series of precipitation for Hungary. The Vienna precipitation values have been multiplied by 0.85 to reflect the seasonality of infiltration (Deák, 2006). The tritium transport models were calibrated by trial-and-error; we continuously adjusted the simulated results to the measured values.

In Méntelek and Fischerbócsa the well-nests were constructed in 1998. During the construction of the wells, soil samples were taken, and then the tritium concentration of the soil moisture were determined (Deák, 2006). The tritium results for the study sites including Nyíradony are shown in Table 1. In case of Méntelek we successfully applied the combination of the tritium-peak method and the numerical transport modelling. The 11 samples

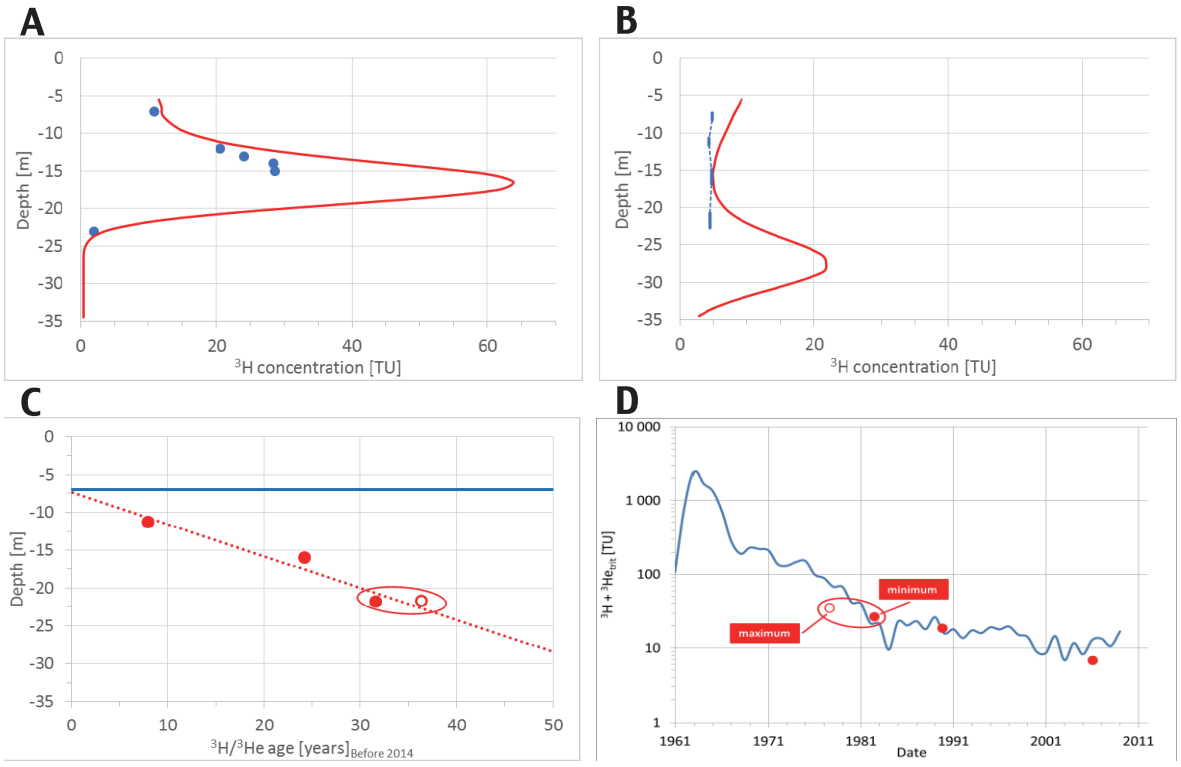

Fig. 4. Results for the Fischerbócsa recharge area: legend as for Fig. 3. Empty circles represent calculated maximum ages and $^3H_{initial}$ *in case of degassed samples.*

from 1998 are apparently sufficient to fit the simulated values (Fig. 3a). The bomb-peak was located at approximately 13 m below the ground surface. This model was the basis for the further modelling (for 2010 and 2014). In 2010 and 2014 we sampled the groundwater at four depths through the screened sections of the four wells. The simulated values are shown in Fig. 3b. According to these models the bomb-peak moved down, and the ^{3}H concentration decreased from the expected value. The blue and purple dashed markers indicate the measured values from 2010 and 2014, while the red and green curves show the simulated values at the same time. During the period of 1998–2010 (about one ^{3}H half-life) the bomb-peak moved down with approximately 5 m, furthermore the ^{3}H concentration decreased due to radioactive decay.

The situation was similar in Fischerbócsa, where groundwater was sampled from six different depths also in 1998 (Fig. 4a). The blue filled circles show the measured values, while the red curve indicates the results of the modelling. It appears that the sample at 15 m below the ground surface does not represent the bomb-peak. Figure 4b shows that the highest tritium concentration, that assumed to be close to the bomb-peak, moved down, and the water samples taken from these depths have a tritium content of 4.5–4.8 TU for 2014. Hence, all of the four groundwater samples indicate water younger than that of the bomb peak. The basis of the model from 2014 was the primarily the model from 1998 along the lines of the procedure used in Méntelek.

At the third research site in Nyíradony the well-nest was constructed in 2014, with the wells being sampled the same year. As Fig. 5b shows, the bomb-peak was not reached at any of the sampled depths. Using transport modelling we fitted the upper part of the simulated curve for the measured values. According to the simulation the location of the bomb-peak is probably at 17.5 m depth, where the modelled magnitude of the ^{3}H concentration is the expected value.

Using the combination of the tritium-peak method and numerical transport modelling the average groundwater recharge rates have been simulated for Méntelek, Fischerbócsa and Nyíradony as 48 ± 6 mm/yr, 62 ± 8 mm/yr and 27 ± 3 mm/yr, respectively for the period 1951–2014. These recharge rates are 8.9%, 11.0% and 4.4% of the annual precipitation amount for each sites.

Another approach was also used to unravel recharge conditions (see Section "Applied Methods" above). ^{3}H/^{3}He apparent ages were calculated from the measured tritium, noble gas concentrations and ^{3}He/^{4}He isotope ratios. Table 2 shows the obtained noble gas values for all research sites. A clear increase in ^{3}He/^{4}He ratios can be seen with depth and is attributed to the accumulation of

tritiogenic ^3He ($^3He_{trit}$) in the groundwater. To calculate $^3H/^3He$ ages, the $^3He_{trit}$ has to be determined. We used the closed-system equilibration excess air model (Aeschbach-Hertig *et al.*, 1999) to describe noble gas partitioning in the liquid and gas phase due to entrapped air bubbles below the groundwater level. The contribution of radiogenic helium was almost negligible, lower than $7 \cdot 10^{-9}$ ccSTP/g (ccSTP: cubic centimetre at standard temperature and pressure). Here we assumed that $^3He/^4He_{rad}$ was $3 \cdot 10^{-8}$. Table 2 shows the calculated $^3H/^3He$ apparent ages, while in Figs. 3c, 4c and 5c the ages are plotted against the sampling depths. The ages increase almost linearly with depth. In some cases, noble gas concentrations showed a degassed pattern, as though some subsurface degassing might have occurred (Visser *et al.*, 2007). In these cases (Fischerbócsa-4, Nyíradony-5 and -6), a minimum and a maximum age were calculated according to Aeschbach-Hertig *et al.* (2008). Based on the calculated initial tritium concentrations, which are the sum of ^3H and $^3He_{trit}$, the minimum ages better match the tritium time series of precipitation than the maximum ages do. It is more pronounced in the case of Fischerbócsa-4 (Fig. 4d). The initial tritium concentrations calculated as the sum of the $^3H_{measured}$ and $^3He_{trit}$ of the minimum and maximum ages of the two groundwater samples in the medium deep wells at Nyíradony, lie on the tritium curve of precipitation (Fig. 5d). However, in this latter case, the minimum ages have been selected for further evaluation since the maximum ages are outliers in the age-depth profile shown in Fig. 5c.

The slope of the linear equations in the age-depth profile provides the vertical flow velocity of the groundwater recharge. To calculate recharges rates at the surface, the effective porosity has to be multiplied with the vertical flow velocity. As mentioned earlier, effective porosity values of 0.15, 0.15 and 0.12 were used for the Méntelek, Fischerbócsa and Nyíradony sites respectively. The $^3H/^3He$ age vs. depth profiles gave us 320 ± 7 mm/yr, 420 ± 9 mm/yr and 171 ± 3 mm/yr average vertical flow velocities, hence the calculated recharge rates are obtained to be 48 ± 6 mm/yr, 63 ± 9 mm/yr and 22 ± 4 mm/yr respectively. These recharge rates agree very well with those obtained from the tritium profile. As a percentage of the annual precipitation, these values correspond to 8.9%, 11.2% and 3.6%, respectively.

To obtain an independent estimation of recharge rate, we investigated the vertical moisture distribution of the unsaturated zone. Approximately 5 m long undisturbed cores were taken from each study site (4.9 m from Méntelek, 4.7 m from Fischerbócsa, 5.3 m from Nyíradony, each 46 mm in diameter). As the unsaturated zone is composed of sand with low clay amount, we assume that the residual and bound water contribution is negligible. Therefore, the sole source of the moisture is

Table 2. The measured noble gas concentrations and the calculated $^3H/^3He$ groundwater ages and $^3H+^3He$ concentrations

Name of the wells	Date of sampling	^3H	$He \cdot 10^8$	$Ne \cdot 10^7$	$Ar \cdot 10^4$	$Kr \cdot 10^8$	$Xe \cdot 10^8$	R/R_a	$^3H/^3He$ age	$^3H+^3He$
		[TU]	[ccSTP/g]						[years]	[TU]
Méntelek-well-1	15.12.2010	5.60 ± 0.16	4.96	1.99	3.68	8.43	1.21	1.02	7.3 ± 1.8	8.4 ± 1.1
Méntelek-well-2	15.12.2010	5.62 ± 0.20	4.52	1.96	3.69	8.59	1.20	1.19	11.4 ± 2.5	10.5 ± 1.1
Méntelek-well-3	15.12.2010	15.04 ± 0.43	4.38	1.94	3.76	8.68	1.22	4.15	32.6 ± 4.5	91.0 ± 3.0
Méntelek-well-4	15.12.2010	4.53 ± 0.14	5.44	2.29	4.01	8.91	1.25	2.79	46.3 ± 4.9	59.5 ± 2.3
Fischerbócsa-well-2	22.05.2014	4.35 ± 0.16	4.70	1.86	3.59	8.23	1.16	1.12	7.9 ± 0.2	6.8 ± 1.4
Fischerbócsa-well-3	22.05.2014	4.75 ± 0.24	4.52	2.00	3.64	8.48	1.22	1.56	24.2 ± 0.7	18.5 ± 1.9
Fischerbócsa-well-4	22.05.2014	4.52 ± 0.15	3.59	1.78	3.70	8.55	1.23	2.35	31.5 ± 4.4 (36.4 ± 4.6)	26.6 ± 2.2 (34.9 ± 3.4)
Nyíradony-well-1	13.03.2014	5.80 ± 0.40	4.71	2.07	3.70	8.35	1.18	1.06	2.4 ± 2.5	6.6 ± 1.3
Nyíradony-well-2	13.03.2014	4.80 ± 0.40	3.96	1.95	3.68	8.45	1.20	1.23	6.6 ± 2.4	6.9 ± 1.3
Nyíradony-well-3	13.03.2014	4.00 ± 0.30	3.62	1.58	3.34	8.16	1.10	1.46	14.3 ± 2.1 (16.4 ± 2.3)	8.9 ± 1.3 (10.1 ± 1.9)
Nyíradony-well-4	13.03.2014	4.10 ± 0.40	2.43	0.06	2.10	5.23	0.88	1.55	18.8 ± 3.5 (23.9 ± 3.7)	11.8 ± 1.3 (14.6 ± 1.8)
Nyíradony-well-5	13.03.2014	7.60 ± 0.50	4.62	2.29	3.76	8.50	1.22	2.70	32.3 ± 1.2	46.7 ± 2.3
Nyíradony-well-6	13.03.2014	18.80 ± 0.60	8.11	3.05	4.64	9.44	1.30	3.51	35.2 ± 0.7	136.5 ± 4.6

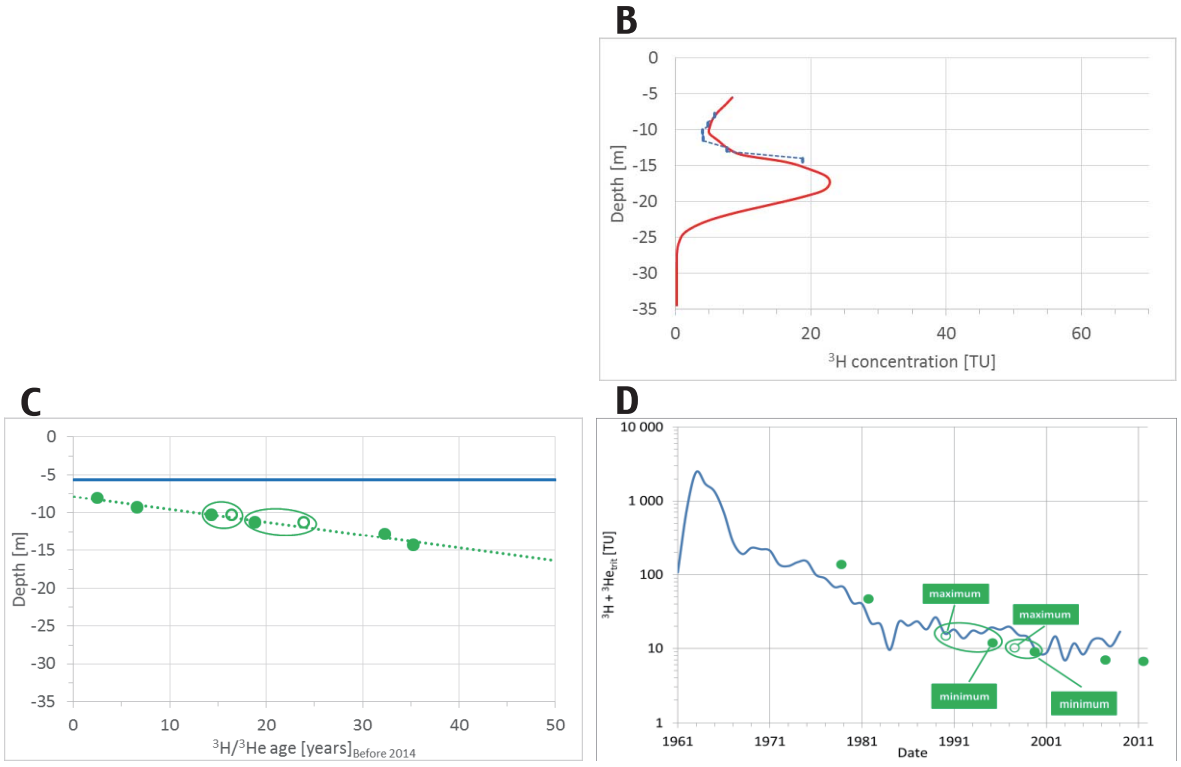

Fig. 5. Results for the Nyíradony recharge area: legend as for Figs. 3 and 4. Top left figure is missing since there were no tritium analyses on soil moisture.

Table 3. Comparison of the recharge rates obtained from different methods (values in parentheses are the recharge rates as the percentage of the annual precipitation amount)

	Méntelek	Fischerbócsa	Nyíradony
Recharge rate using ^{3}H peak	48 mm/yr (9%)	62 mm/yr (11%)	27 mm/yr (4%)
Recharge rate using ^{3}H/^{3}He age profiling	48 mm/yr (9%)	63 mm/yr (11%)	22 mm/yr (4%)
Long term annual precipitation (1985–2015)	541 mm/yr	565 mm/yr	607 mm/yr
Recharge rate using moisture distribution of the unsaturated zone	54 mm/yr (8%)	28 mm/yr (4%)	43 mm/yr (10%)
Recent annual precipitation (2014–2015)	672 mm/yr	669 mm/yr	440 mm/yr

recent recharge. Each core was divided into subsamples of 10 cm, the water content was distilled from the sand, and then the oxygen stable isotope composition was determined to look for a seasonal pattern and to calculate the duration of the vertical water movement in the unsaturated zone. In each soil core, the oxygen isotope distribution shows a clear seasonal pattern, hence the transit time could be determined (Landon *et al*., 1999; Gazis and Feng, 2004). Knowing the residence time of the water in the unsaturated zone, the overall moisture content in the soil core can be converted to a recharge rate. For the Méntelek, Fischerbócsa and Nyíradony sites, we obtained 12, 18 and 24 months for the transit time, and 90.2, 69.2, 143.6 g for the soil moisture, respectively. Using these values, the recharge rates can be calculated. All details of the investigation of the hydrodynamic behaviour of the unsaturated zones in the three study sites will be published elsewhere, however, here we compare the recharge rates obtained from (i) ^{3}H bomb-peak; (ii) ^{3}H/^{3}He apparent age profile; and (iii) soil moisture distribution. As Table 3 shows, recharge rates in Fischerbócsa calculated either from the ^{3}H, ^{3}H/^{3}He or the soil moisture approach agree very well. However, for the two other sites the obtained recharge rates have larger differences. Although, the tritium peak method and the ^{3}H/^{3}He method gave similar values, the calculation based on the soil moisture gave smaller and higher recharge rates for Fischerbócsa and Nyíradony, respectively. These two latter cases suggest

that the moisture content of the unsaturated zone provides recharge information only for the most recent years. While further investigation is needed to recover the relationship between climate and the hydrology of the unsaturated zone, the differing recharge rates could be explained by the last decade being the warmest so far of modern times, including a particularly hot final year, hence evapotranspiration may have played a significant role in the water cycle in the last few years while the infiltrating water was passing through the unsaturated zone. The recharge rates in Table 3 can be considered as prevailing hydrological parameters for the Great Hungarian Plain.

Conclusion

The present study has investigated the natural groundwater recharge to the saturated zone through sandy soils on regional recharge areas in Hungary using isotope hydrological tools and transport modelling. The tritium peak method gave recharge amounts of 8.9%, 11.2% and 3.6% respectively of the annual precipitation, while the $^3H/^3He$ technique gave the very similar results of 8.9%, 11.0% and 4.4%. A third approach using the stable isotope content of soil moisture agreed much less well. It is inferred from the results that while the tritium peak method works best for earlier decades, and the isotope-moisture method for very recent years, the most reliable method overall is the $^3H/^3He$ technique.

Although this study has investigated only three local sites in two large recharge areas, the consistent recharge rate information obtained is of great significance for the whole system. It indicates that to estimate the sustainable water resources in similar recharge areas, environmental tracers such as isotopes should be used in addition to the more standard hydrological tools. The successful deployment of tritium/helium-3 dating in this study also suggests that it could usefully be extended to other types of recharge environment, including sedimentary and karst recharge areas.

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