REMOTE-SENSING BASED GROUNDWATER RECHARGE ESTIMATES IN THE DANUBE-TISZA SAND PLATEAU REGION OF HUNGARY

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Mean annual recharge in the Danube-Tisza sand plateau region of Hungary over the 2000–2008 period was estimated at a 1-km spatial resolution as the difference of mean annual precipitation (P) and evapotranspiration (ET). The ET rates were derived from linear transformations of the MODIS daytime land surface temperature (T_s) values with the help of ancillary atmospheric data (air temperature, humidity, and sunshine duration). The groundwater under the sand plateau receives about 75 ± 50 mm of recharge annually (the plus/minus value is the associated error, resulting from an assumed 5% error in both the P and ET values), which is about 14 ± 9 % of the regional mean annual P value of 550 mm. The largest continuous region with elevated recharge rates (about 180 ± 50 mm a^{-1} or 30 ± 8 % of P) occur in the south-western part of the plateau due to more abundant precipitation (around 580 mm a^{-1}), while recharge is the smallest (about 40 ± 40 mm a^{-1} or 7 ± 7 % of P) under forested areas. Typically, lakes, wetlands, river valleys, and certain afforested areas in the north-central part of the region act as discharge areas for groundwater.

KEY WORDS: Groundwater Recharge, MODIS Data, Danube-Tisza Sand Plateau.

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Priemerný ročný úhrn doplňovania podzemných vôd plošiny zloženej z pieskov medzi riekami Dunaj a Tisa s rozlíšením 1 km, pre roky 2000–2008 bol určený ako rozdiel medzi priemerným ročným úhrnom zrážok (P) a evapotranspiráciou (ET). ET bolo určené z lineárnej transformácie teploty povrchu počas dňa (T_s) získanej systémom MODIS pomocou údajov o vlastnostiach atmosféry (teplota vzduchu, vlhkosť vzduchu a trvanie slnečného svitu). Podzemná voda pod pieskovým masívom dostáva ročne asi 75 ± 50 mm vody (znamienka plus/mínus znamenajú chybu, vyplývajúcu z predpokladanej 5% chyby hodnôt P a ET), ktorá je asi 14 ± 9 % regionálnej priemernej ročnej hodnoty P, ktorá je 550 mm. Najväčšia spojitá oblasť so zvýšeným doplňovaním podzemnej vody (približne 180 ± 50 mm za rok alebo 30 ± 8 % P) sa nachádza v juhozápadnej časti plató a je dôsledkom vyššieho ročného úhrnu zrážok (okolo 580 mm), doplňovanie je nižšie v zalesnených oblastiach (okolo 40 ± 40 mm, alebo 7 ± 7 % P). Jazerá, mokrade, rieky a niektoré zalesnené oblasti v strednej a severnej časti tejto oblasti drénujú podzemné vody.

KĽÚČOVÉ SLOVÁ: doplňovanie podzemných vôd, MODIS, plató Dunaj-Tisa.

Introduction

The Danube-Tisza interfluvial sand plateau of Hungary (Fig. 1) has been in the focus among water resources and agricultural managers for several decades due to its declining groundwater levels. Since the 1970's, the groundwater table in the region has been sinking steadily, reaching a new equilibrium by the mid 1990's, about 2–3 m below its previous level (*Pálfai*, 2010). The reasons for this decline have been identified (*Szilágyi* and *Vörösmarty*, 1997; *Pálfai*, 2010) as climatic (predominantly a less favorable precipitation regime between 1970–1990), and man-made (increases in forest cover due to planned afforestation and an increase in semi-confined groundwater extraction leading to induced replenishment from the overlying unconfined aquifer). The relative weights of the above causes are still debated. Based on a complex surface water-ground water model of the region, *Szilágyi* (1994), *Szilágyi* and *Vörösmarty* (1997) estimated the undisturbed (i.e., before the 1970's)

mean annual groundwater recharge to be about 50 mm a^{-1}. In the present study this recharge estimate is revisited for the 2000–2008 period, based on the latest developments in remote sensing technology for water resources applications (*Szilágyi* and *Kovács*, 2010, 2011).

Fig. 1. Location of the sand plateau region within Hungary. The letter K marks the town of Kecskemét for which climate data is displayed in Tab. 1.

Study-site description

The sand plateau region of Hungary has an approximate (depending on where the northern limit is drawn) extent of 15 000 km^2. It is bordered by the Danube from the west, by the Tisza and Zagyva Rivers from the east and north-east, respectively, by the Gödöllö Hills from the north, and by the state border in the south (Fig. 2). The plateau is about 30–50 m higher than the flanking flood plains and due to its porous sandy soils and relatively smooth relief most of the annual precipitation of about 550 mm (Fig. 3) seeps into the ground (to contribute to deep percolation or evapotranspiration), resulting in negligible surface runoff. The groundwater table is typically within 3–6 m of the ground. The unconfined and the underlying semi-confined aquifer are connected by a semi-permeable aquitard allowing for seepage between the two aquifers. The climate is continental, with a mean annual temperature of about 10 °C and with precipitation more or less evenly distributed throughout the year (*Péczely*, 1981) expressing a slight maximum in the spring/early summer and a minimum in winter (Tab. 1). Dominant land use in the area is agricultural, with a significant presence of forests (most of them planted), which doubled in extent over the past 80 years, to reach 20–25% of the total area by 2000.

The porous sand plateau, due to its minimal surface runoff, and flat-to-rolling topography is an ideal place to estimate mean annual recharge rates as the difference in precipitation and evapotranspiration (ET) over a sufficiently long period so that the change in soil moisture becomes negligible in comparison with the cumulative fluxes across the surface. The Moderate Resolution Imaging Spectroradiometer (MODIS) data, freely available from the internet (http://modis.gsfc.nasa.gov/) is almost ideal for the present purpose because it has been collected over a decade now at a nominal spatial resolution of about 1 km. With the help of MODIS daytime surface temperature and ancillary climate data, ET at 1-km resolution has been mapped for Hungary by *Szilágyi* and *Kovács* (2010, 2011). A short summary of the approach is discussed below.
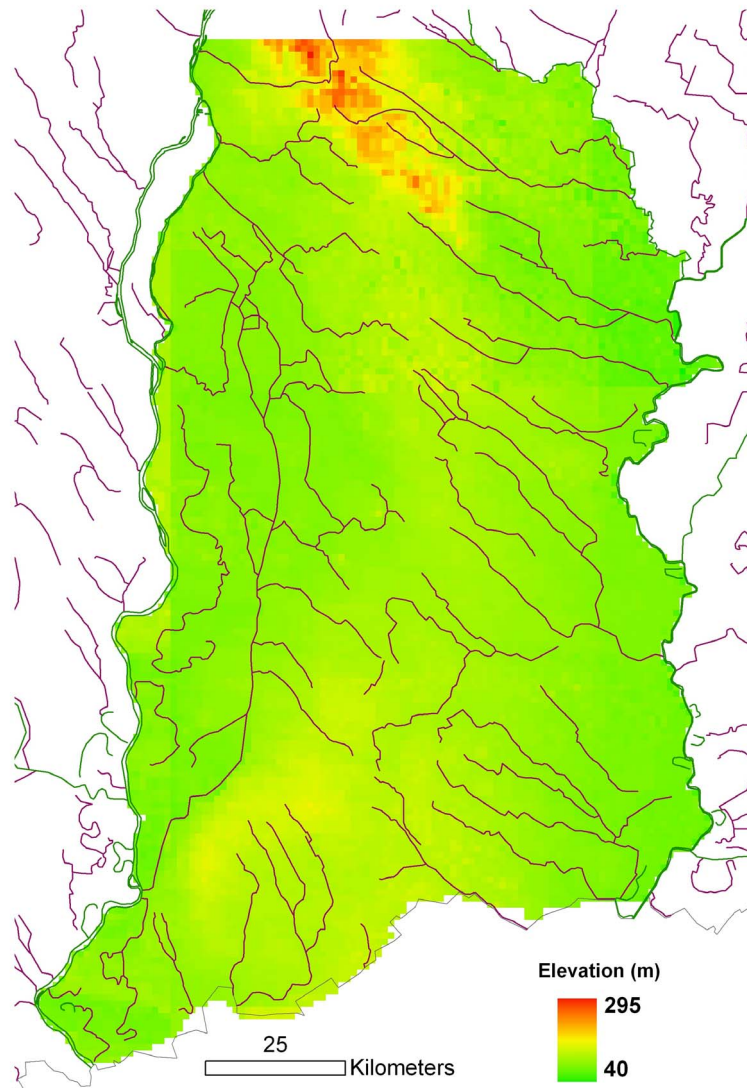
Fig. 2. Elevation and stream network of the sand plateau.

Description of the ET mapping approach

Based on standard climate data, *Morton* et al. (1985) presented an algorithm (called the WREVAP model) for estimating regionally representative *ET* rates for periods longer than 5 days. *Szilágyi* and *Józsa* (2009), *Szilágyi* et al. (2011) devised a method of disaggregating the regional *ET* values into spatially variable *ET* rates based on the assumption that at a large enough scale (i.e., at or larger than 1 km) where surface heterogeneities of a rolling terrain become largely smoothen out, surface temperatures are proportional to the actual *ET* rates, since evaporation is an endothermic process, providing an effective cooling (due to the high latent heat of vaporization) of the evaporating surface. The spatial disaggregation of the regionally representative evapotranspiration rate, $<ET>$, is based on a linear transformation of the 8-day composited MODIS daytime surface temperature (T_s) values into pixel *ET* rates. The transformation requires the specification of two anchor points in the T_s versus *ET* plane. The first anchor point is defined by the spatially averaged daytime surface temperature, $<T_s>$, and the corresponding regionally representative *ET* rate, $<ET>$, from WREVAP, using spatially averaged values of the required climate variables. The second anchor point comes from the coldest, or a spatial average of the coldest, pixel values, $<T_{sw}>$, within the region and the corresponding wet environment evaporation rate, out of consideration that the coldest pixels are the wettest,
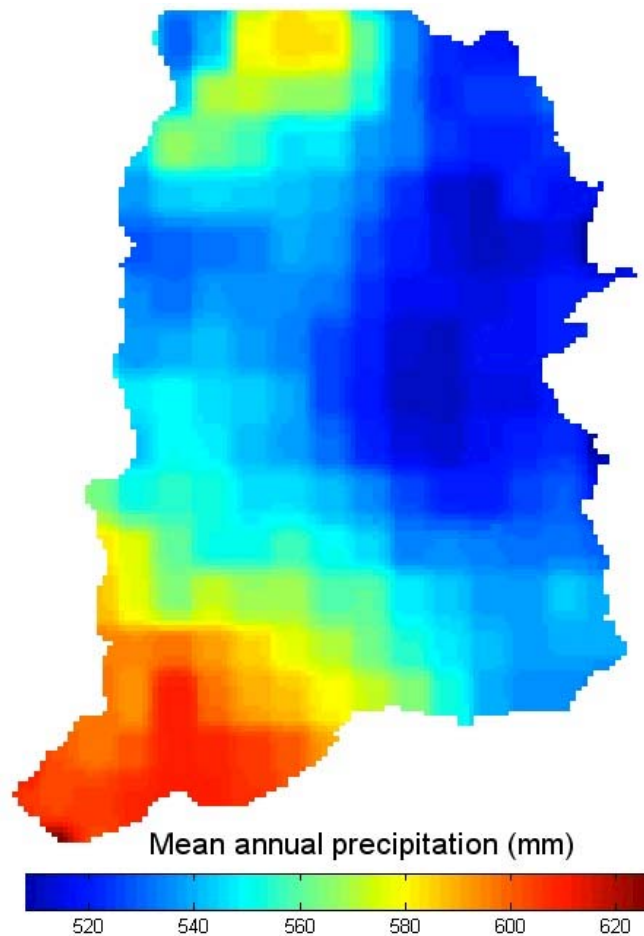
Fig. 3. Period averaged (2000–2008) mean annual precipitation rates [mm] over the sand plateau.

T a b l e 1. Long-term mean monthly precipitation [mm] and air temperature [°C] values at Kecskemét (Fig. 1), near the center of the Danube-Tisza region (after *Péczely*, 1981). The precipitation values in parenthesis are for the 2000–2008 period.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Temperature	−1.7	0.1	5.1	10.5	16	19.3	21.4	20.6	16.3	10.6	4.6	0.6
Precipitation	26	29	32	45	56	55	48	45	46	48	50	37
	(27)	(32)	(35)	(39)	(44)	(67)	(70)	(53)	(46)	(32)	(35)	(36)

evaporating at the wet environment *ET* rate, E_w (*Priestley* and *Taylor*, 1972). Note that at the 1-km scale of the MODIS pixels this is the largest evapo-ration rate possible (*Brutsaert*, 1982). The two points define the linear transformation of the T_s pixel values into *ET* rates for each 8-day period, or, as was done by *Szilágyi* and *Józsa* (2009) and re-peated here, for each month by employing monthly means of the required variables. The resulting T_s versus *ET* line each month is extended toward the highest T_s values, since in about half the number of the pixels *ET* is less than the regional *ET*. A month-ly time-step is ideal since most of the watershed – or large – scale hydrologic/ecological models work at this time-resolution, plus a monthly averaging

further reduces any lingering cloud effect in the 8-day composited T_s values. The method produces ET estimates typically within 10% of measured month-ly or water-balance derived annual and multi-annual values (*Móricz*, 2010). For further infor-mation and validation of the method, see *Szilágyi* and *Kovács* (2010, 2011) and *Szilágyi* et al. (2011).

8-day composited MODIS daytime surface tem-perature data were collected for Hungary over the 2000–2008 period and were averaged for each month to yield one surface temperature per pixel per month. Mean annual precipitation, mean monthly air temperature, specific humidity as well as sunshine duration values were provided by the Hungarian Meteorological Service in the form of

grid-data. The transformations were performed from March till November each year, because in the winter-time with possible patchy snow cover on the ground the quasi-constant surface net energy assumption of the T_s versus ET transformations break down (*Szilágyi* and *Józsa*, 2009). This does not seriously hinder the calculation of annual ET values, since ET in Hungary is small from December through February due to typical air temperatures around the freezing point and dormant vegetation.

Mapping mean annual recharge

Mean annual recharge is estimated as the difference in mean annual precipitation (P) and ET due to the special characteristics (i.e., flat-to-rolling terrain, highly permeable sandy soils) of the sand plateau region of Hungary. Both variables are obtained with a 5% accuracy at best (*Dingman*, 2002). After extensive testing with data from four continents, Morton reported (*Morton*, 1983) the regionally representative multi-year ET estimates of WREVAP to agree within 10% of water-balance data, which, considering the possible error in areal precipitation estimates and stream discharge measurements, is a considerably good estimate. Note that due to the construction of the T_s versus ET transformation, the pixel ET values, when averaged over a large area, yield the regional ET value. However, a 5% error in the precipitation and ET variables, occurring independently may lead to a 10% error in the P minus ET value, and considering that ET (with a regionally averaged mean annual rate of about 470 mm) in the sand plateau is between 80–90% of precipitation at most locations (Fig. 4), it can lead to a ± 45–95% error in the resulting recharge estimates. To characterize this uncertainty, an assumed 5% error will be kept in the mean annual P and ET estimates throughout the study. The present estimation of the mean annual recharge rates assumes no significant trends in soil moisture (thus, in the groundwater table elevations) over the study period of 2000-2008, which is valid to a large degree (*Pálfai*, 2010), since after around 1995 (till present) the groundwater table stabilized at a level of about 2–3 m lower than was previously observed, i.e., before the 1970's.
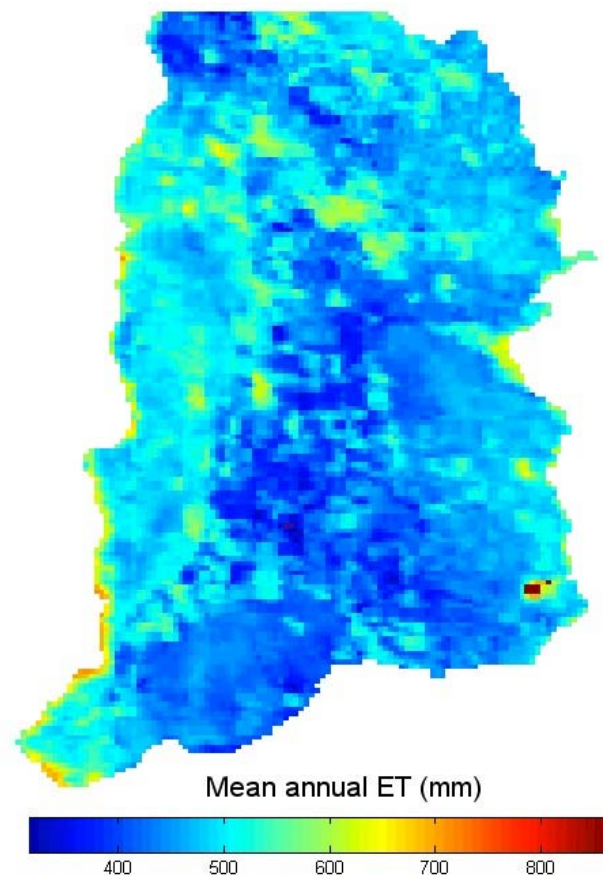

Fig. 4. Estimated period averaged (2000–2008) mean annual ET rates [mm] over the sand plateau.

Results and discussions

Distribution of the mean annual recharge rates to the groundwater over the study area is displayed in Fig. 5. The mean annual recharge rate is 75 ± 50 mm, which is about 14 ± 9 % of the precipitation the area receives. The largest continuous area with the highest rates ($150 \pm 50 - 200 \pm 50$ mm a^{-1}) is found in the south-western part of the region, where precipitation rates are the largest (Fig. 3), forest cover is scarce (Fig. 6), and depth to groundwater is large (> 5 m, *Pálfai* (2010)). From a comparison of Fig. 6 with a depth-to-groundwater map of *Pálfai* (2010), it can be stated that the estimated recharge rates are the largest where depth to the groundwater table is relatively large (> 3 m) and the land cover is not forest. From an analysis of the *ET* and re-charge rates, according to land cover (obtained from the CORINE (*EEA*, 1994) data set at http://www.eea.europa.eu/themes/landuse/

interactive/clc-download), *ET* is largest, about 505 mm a^{-1}, over deciduous forests, therefore, recharge is the smallest, about 40 ± 40 mm a^{-1}. Naturally, forests with their more developed, dense root sys-tem can capture a larger part of the infiltrated water than other land cover types. Often, the root system of vegetation can be so developed and/or the groundwater-table so close to the surface, that it can tap the saturated zone, thus leading to elevated *ET* rates, frequently surpassing the precipitation rate the area receives. Fig. 6 displays the locations (in magenta) where *ET* is estimated to be larger than precipitation. On many locations these groundwater discharge areas overlap with a forest cover (deep green areas), especially in the north-central part of the study region. Typically, these groundwater dis-charge areas appear, beside these forested locations, under lakes, marshes, wetlands, and river valleys where the groundwater table is close to the surface (< 3 m) thus letting almost any vegetation type to reach it.
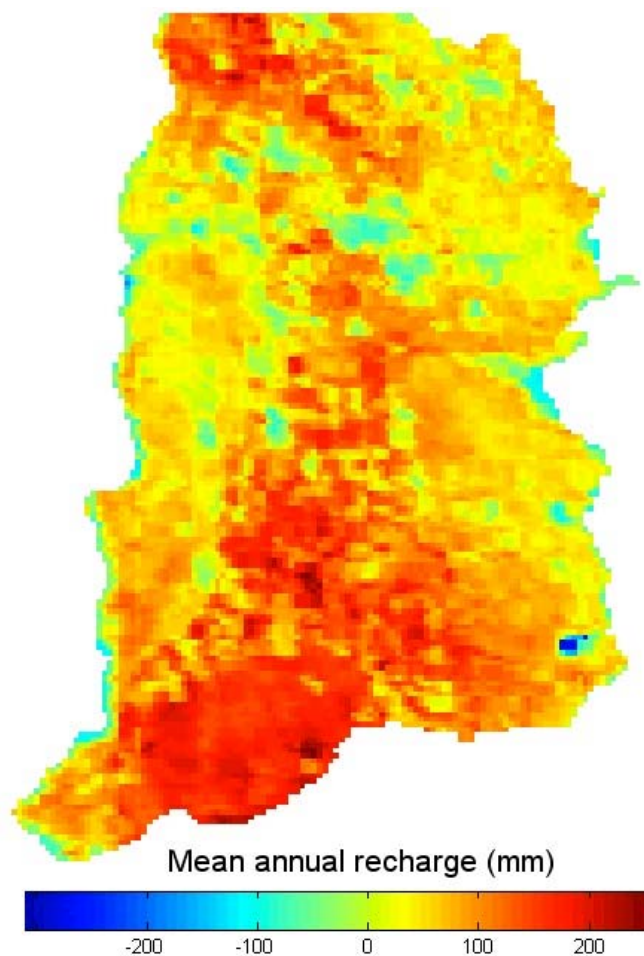

Fig. 5. Mean annual recharge [mm], estimated as the difference in period averaged (2000–2008) mean annual precipitation and ET over the sand plateau.
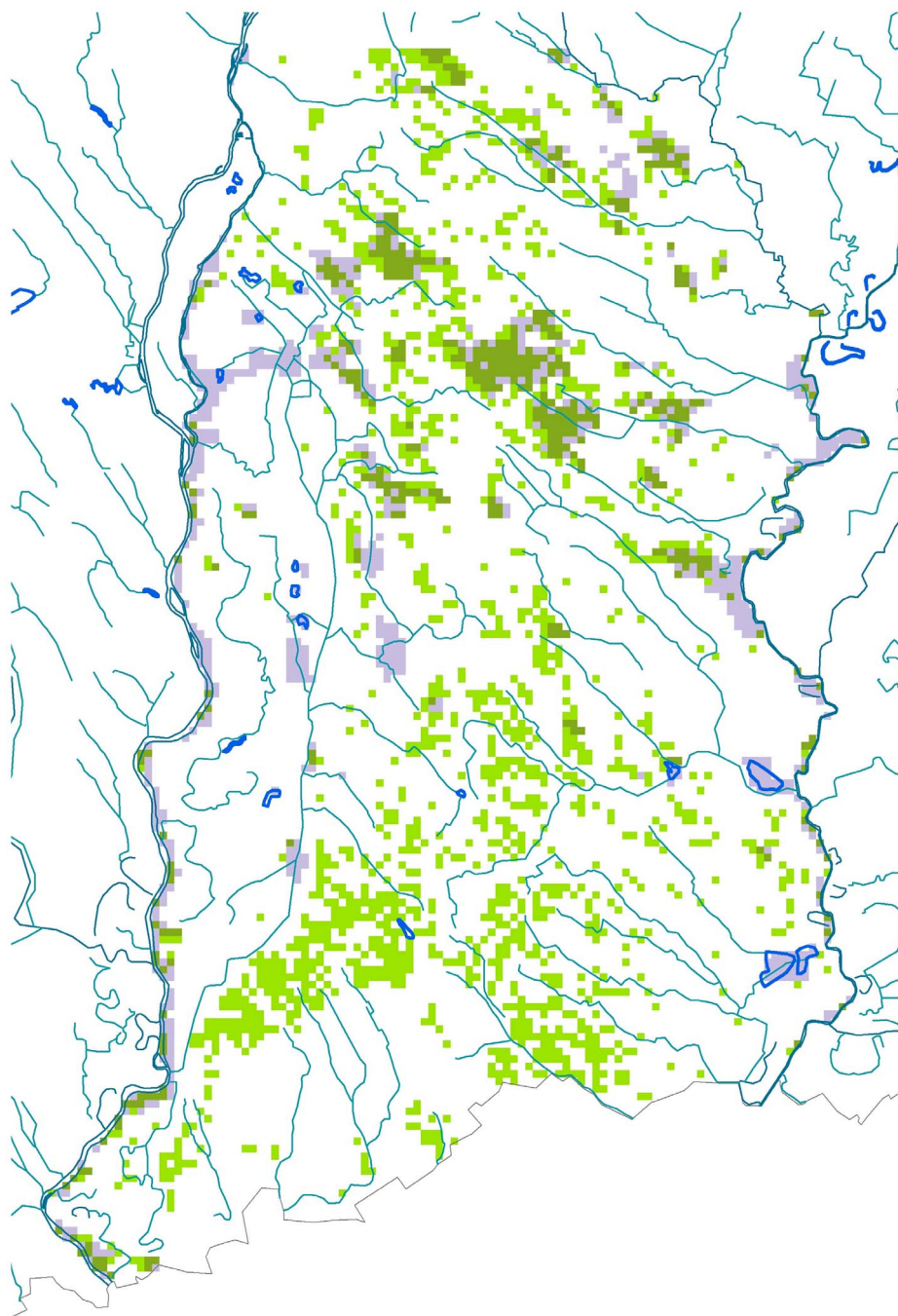
Fig. 6. Distribution of the groundwater-discharge areas (i.e., estimated recharge is negative, in magenta) together with the forests (light green). The forest is indicated in dark green where the two areas overlap. Lakes are outlined in vivid blue color.

Having a groundwater ridge around the central axis of the sand plateau, forests can only consume more water than they receive from precipitation if they create a local depression in the groundwater table, to induce groundwater flow directed toward them, which thus supplies the difference in *ET* and precipitation. In fact, this has been reported by *Major* (1976, in *Stelczer*, 2000) who found that under a young forest in the region the groundwater table was on average 1 m deeper than in the surrounding non-forested areas. They calculated a mean annual *ET* rate of 712 mm for an actively growing black

spruce community covering an area of 500 x 500 m. On average the forest consumed 130 mm more water annually than it received from precipitation. The current estimates of *ET* rates match these findings, yielding an average 620 mm annual *ET* for the forests in the groundwater discharge areas (this value may go up to 650 mm in certain pixels), which is about 80 mm more than the mean annual precipitation rate of the region.

The present, regionally representative mean annual recharge estimate of 75 ± 50 mm is 50% higher than the previous 50 mm a^{-1} estimate of *Szilágyi* (1994) and *Szilágyi* and *Vörösmarty* (1997) for the undisturbed (before groundwater declines took place) 1951–1970 period, although the error bounds include the latter estimate. Precipitation has remained practically the same over the two periods: 560 mm for 1951–1970, and 550 mm for 2000––2008, however its distribution may have changed within the year (Tab. 1), thus influencing the resulting recharge rates. In the complex model of *Szilágyi* (1994) recharged water in the 1951–1970 period could only leave the area through seepage toward the Danube and the Tisza Rivers. In reality, however, the area is drained by many smaller streams and canals (Fig. 2) the effect of which included in the present recharge estimate. *Major* et al. (1991), lacking continuous discharge measurements on the small streams of the plateau, estimated this drainage to be 12 mm annually for the southern part of the region. Adding to this number the estimated (*Davideszné*, 1991) induced seepage of 10–20 mm annually from the unconfined groundwater system toward the underlying semi-confined one, due to a significant level of water extraction from the latter aquifer (becoming significant from the 1970s on (*Pálfai*, 2010), the two estimates, i.e., 75 ± 50 and 77 mm a^{-1}, match very closely. The induced seepage in general lowers the unconfined groundwater level leading to reduced soil moisture and therefore to reduced plant transpiration and so to increased recharge. Interestingly, the intervening 1970–1995 period is the one when precipitation decreased by about 7–8%, and semi-confined groundwater extractions grew three-fold, leading predominantly to the reported 2–3 m unconfined groundwater level decline over the same period. To a lesser extent, increases in forested areas with their enhanced ET rates also contributed to the decline (*Szilágyi*, 1994).

The estimated mean annual recharge rate of 75 ± ± 50 mm in the sand plateau is practically identical to that (73 ± 50 mm or 14 ± 9 % of the precipita-

tion) of another, regionally significant, high permeability area, the Sand Hills of Nebraska, USA, the largest sand-dune region of the western hemisphere with a similar continental climate (mean temperature of 10 °C, and annual precipitation of 533 mm), obtained with the same method (*Szilágyi* et al., 2011). In the Sand Hills these recharge estimates were corroborated by findings of *Clover* (1972) and *Chen* and *Chen* (2004) who, via calibrating a hydrogeology model of the unconfined groundwater system against observed groundwater-table elevations and stream discharges, reported an estimated mean annual recharge rate of 69 mm or 13% of precipitation in the central part of the region.

In summary, it can be stated that the present method may be applicable for estimating spatially distributed mean annual recharge rates in sandy areas of the world where basic climate data (precipitation, air temperature and humidity, global radiation or sunshine duration) for the past decade (the temporal coverage of the MODIS data) are available. The WREVAP FORTRAN code, with the corresponding documentation, can be downloaded from the personal website of the first author (snr.unl.edu/szilagyi/szilagyi.htm). The advantage of the present method of estimating mean annual recharge rates is that it (a) provides spatially varying values, thus the effect of land use and vegetation distribution to recharge rates becomes identifiable; (b) requires only typically easily accessible remotely sensed and standard climate data, and; (c) is self-calibrating. The only serious disadvantage of the present method is that the resulting recharge-rate estimates will have a high associated uncertainty level in arid and semi-arid regions where a large portion of the precipitation ends up as *ET*.

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