J. Hydrol. Hydromech., *45*, 1997, 5, 328—347

MODELLING UNCONFINED AQUIFER LEVEL REDUCTIONS IN THE AREA BETWEEN THE DANUBE AND TISZA RIVERS IN HUNGARY

JOZSEF SZILAGYI AND CHARLES VOROSMARTY

The area between the Danube and Tisza Rivers (approximately 15,000 km^2) is the recharge area of a large regional aquifer. Beginning in the early 1970's lower ground water levels (1–3 m drop by 1992) in unconfined aquifers and reduced total hydraulic head in confined aquifers were observed. To test the possible mechanisms responsible for regional-scale reductions in the unconfined groundwater levels, a coupled, distributed-parameter Water-Balance/Groundwater Model was developed and the following model results were obtained: (1) Reforestation, reduction in precipitation and its unfavorable distribution throughout the year during the period 1971–1992 caused an average 50–60 cm (i.e. 35%) decrease in the unconfined groundwater-table elevation. (2) Up to 65% (i.e. an average 1–1.5 m) of the recorded unconfined groundwater decline can be attributed to water extraction from both the confined and unconfined aquifers plus hydrocarbon mining in the southern part of the region.

KEY WORDS: Regional Scale Water-Balance, Distributed Hydrologic Model, Groundwater.

József Szilágyi, Charles Vörösmarty: Modelovanie zníženia hrúbky zvodne v oblasti medzi riekami Dunaj a Tisza v Maďarsku. Vodohosp. Čas., *45*, 1997, 5; 20 lit., 13 obr.

Oblasť medzi riekami Dunaj a Tisza (približne 15 000 km^2) je oblasťou doplňovania veľkej, regionálnej zvodne. Začínajúc rokom 1970 bolo pozorované zníženie úrovne hladín podzemých vôd (zníženie 1–3 m do roku 1992) a tiež zníženie tlakovej výšky v tlakových horizontoch zvodne. Navrhli sme matematický model vodnej bilancie podzemných vôd, aby sa dali posúdiť mechanizmy spôsobujúce zníženie úrovní hladín podzemných vôd v regióne. Získali sme tieto výsledky: 1. Zalesnenie,

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zníženie úhrnov zrážok a zmeny v ich rozdelení počas roka v období 1971–1992 spôsobili zníženie 50–60 cm hrúbky zvodne (30 %). 2. Až 65 % (t.j. asi 1–1,5 m) zníženie hladiny podzemnej vody môže byť spôsobené odberom vody a banskou činnosťou v južnej časti oblasti.

KĽÚČOVÉ SLOVÁ: vodná bilancia regiónu, rozčlenený hydrologický model podzemných vôd.

Introduction

The Danube—Tisza region in central Hungary, with an approximate area of 15,000 km^2, is a major agricultural area producing fruit, vegetables and wine. Agriculture is the only income source for most of the region's 800,000 inhabitants. Unfortunately, their livelihood has been jeopardized in recent decades by changes in water availability due to the decline of the unconfined groundwater levels (Fig. 1). Since the early 1970's, groundwater levels declined steadily and in many parts of the area they are now 2–3 m, and in some locations 4–5 m below previous levels (Palfai, 1993). In the central part of the region the head losses are more pronounced, while near the eastern and western boundaries of the region these declines are less dramatic. The consequences of the groundwater decline are severe. The number and extent of open water surfaces are shrinking year by year. Many of the smallest ponds have become completely dry, as well as the majority of wetlands (Palfai, 1993). Many fish ponds that once produced a large quantity of freshwater fish for human consumption have been eliminated. The nature reserve areas around wetlands, unique in Central-Europe, are in extreme danger and it is doubtful whether they can sustain their original ecosystems.

Hundreds of dug-out wells scattered over the region are running dry, thus restricting water use for agriculture. The recent decline in unconfined groundwater reserves has been accompanied by a substantial decline in total hydraulic head in the underlying confined aquifers. The extent of this decline is over 20 m in approximately 30% of the region and reaches more than 25 m in some places. So severe is the effect that former artesian wells currently need mechanical pumps to bring the water to the surface (Major – Neppel, 1988). To further complicate the picture, Hungary was hit by severe droughts in the past decade, which accelerated the recession of groundwater in the study area and caused unprecedented losses in agricultural production. The loss resulting from the drop in agricultural production reached

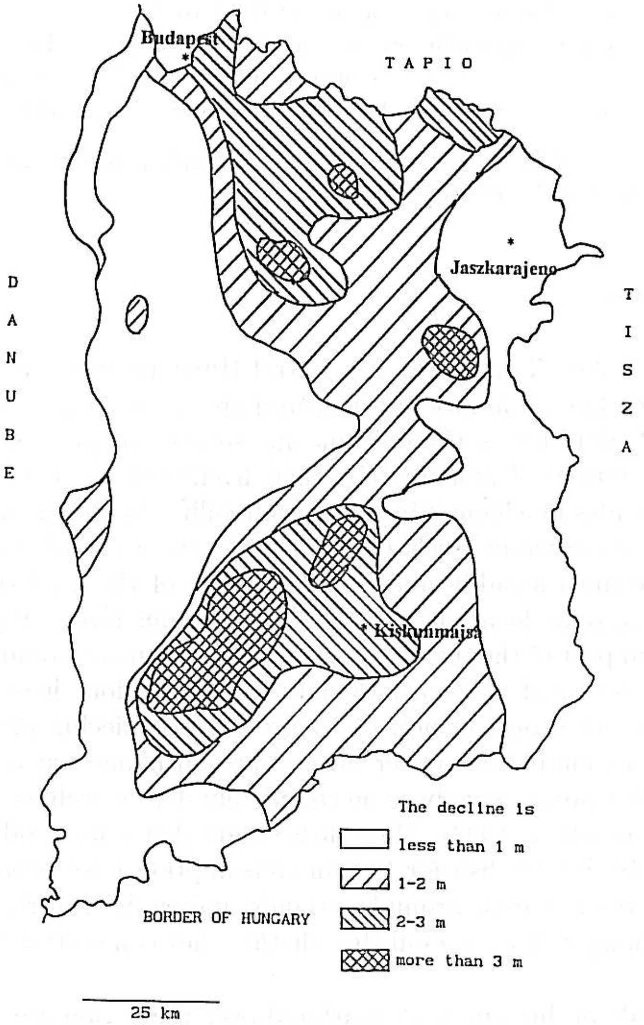

Fig. 1. The areal distribution of the unconfined groundwater decline during the period 1971–1992 (After Palfai, 1993).
Obr. 1. Rozdelenie zníženia hladín podzemných vôd v rokoch 1971–1992 podľa Pálfaia (1993). ▭ menej ako 1 m, ▩ viac ako 3 m.

5 billion forints ($50 million US) in 1992 alone. A drought of the same magnitude occurred in 1983 as well. Palfai (1993) estimates the total loss in the past decade at around 20 billion forints ($200 million US).

If the recent trend continues, major social tensions are likely to develop among the people inhabiting the Danube—Tisza region and potential migration of the population to other already densely-populated parts of the country can be expected (Palfai, 1993).

Study-site description

The study area is bordered on the north by the Tapio River, a tributary of the Tisza River, on the west by the Danube, on the east by the Tisza, a tributary of the Danube and on south by the border of Hungary with Serbia (Fig. 1).

The plateau between the Danube and the Tisza is higher by some 30 to 50 m than the flood plains of the two rivers. During the Pleistocene the Danube crossed the region obliquely between the two present-day rivers, in a braided pattern of branches characteristic of steppe rivers (Pecsi and Sarfalvi, 1964). The frequently shifting branches deposited huge quantities of gravel, sand and fine sediment. Most of the plateau is now covered with windblown sand, blown out of the late Pleistocene alluvial fan of the Danube

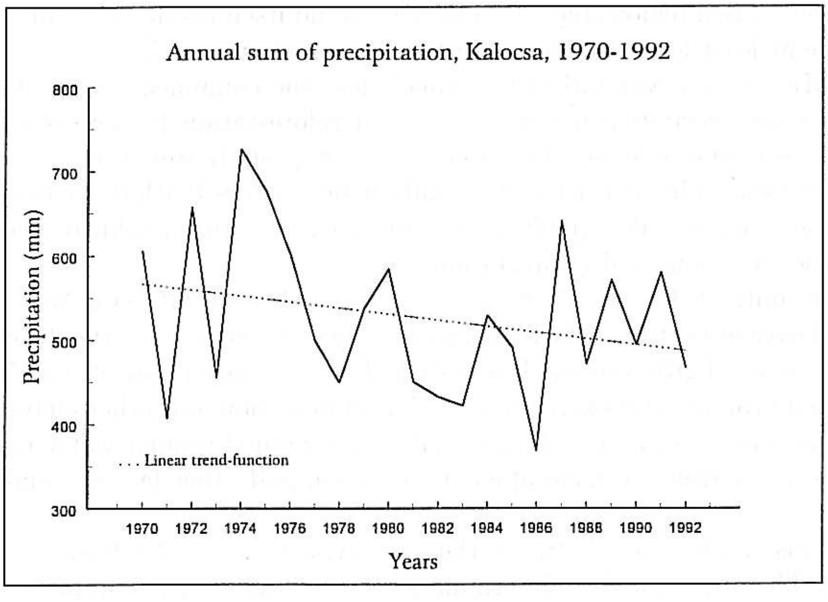

Fig. 2. Annual precipitation [mm] near the center (Kalocsa) of the Danube—Tisza region for the period 1970–1992.
Obr. 2. Ročné úhrny zrážok [mm] v blízkosti centra oblasti Dunaj – Tisza (Kalocsa) v rokoch 1970–1992.

and arranged in dunes by the winds of the Wurmian and early Holocene (Pecsi, 1961; Pecsi and Sarfalvi, 1964; Stefanovits, 1981).

These sand layers contain the unconfined groundwater. An interesting feature of these layers is the connection of the unconfined groundwater over most of the region to the underlying confined aquifers. Because the aquitard between the two aquifers is semi-permeable, this allows water to move between the two different aquifers. The sand and gravel layers underneath the aquitard were deposited in the Pliocene or in earlier geological times.

Relevant previous research conducted in Hungary

Liebe (1990) suggested that the former water-balance of the area had been disturbed by decreasing precipitation since 1970 (Fig. 2) and by the seepage directed toward the confined aquifers due to excessive groundwater extraction from those aquifers. Berenyi and Erdelyi (1990) concluded that the main reason for the groundwater decline was excessive pumpage from the deep, confined aquifers (Fig. 3). Major (1990), and Major and Neppel (1988) stated that the intensive reforestation typical for the entire Danube—Tisza region since 1935 to date, could itself result in groundwater decline at least locally underneath the reforested areas (Fig. 4).

Major and Neppel (1988) concluded: the combined meteorological (decreasing precipitation since 1970) and reforestation influences cannot solely be responsible for the observed lower groundwater levels. The decline is induced by at least three simultaneous factors (with decreasing importance): large-scale exploitation of groundwater from confined reserves, climatic variations and reforestation.

In contrast, Palfai (1992), using factor analysis results, concluded that the relative importance of the different factors contributing to the decline of the unconfined groundwater levels are as follows: climatic variations (50%), confined groundwater extraction (25%), reforestation and other changes in land use (10%), drainage channels (7%), unconfined ground water extraction (6%), petroleum, natural gas production, and other factors combined (2%).

This discrepancy between the two hypotheses is the basis for this study. The objective is to determine whether changes in precipitation patterns and newly grown forests are the greatest contributors to the decline (Palfai 1992), or whether confined groundwater extraction is most important (Major and Neppel, 1988; Berenyi and Erdelyi, 1990).

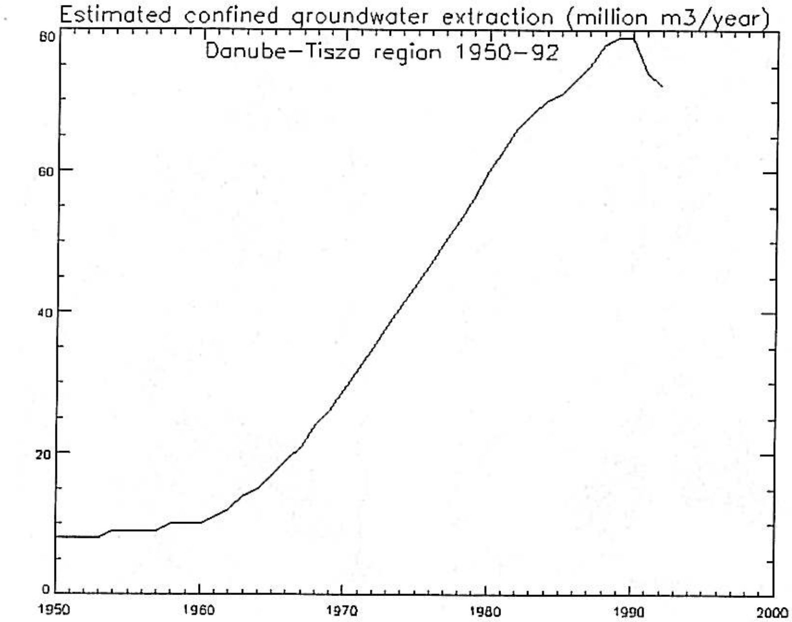

Fig. 3. Estimated total annual amounts (million m^3) of groundwater extracted from the Danube—Tisza region in the period 1950–1992 (After Palfai, 1993).
Obr. 3. Celkové množstvo vody [mil.m^3] odobraté z podzemných vôd oblasti Dunaj – Tisza v rokoch 1950–1992 (podľa Pálfaia, 1993).

Description of the Water-Balance/Groundwater Model (WB/GWM)

A coupled Water-Balance/Groundwater Model was constructed to investigate the effects of the following factors on the groundwater system in the Danube—Tisza region: reforestation, climatic variability, confined and unconfined groundwater extraction including the effects of hydrocarbon production.

The Water-Balance Model component was originally developed by Vorosmarty (Vorosmarty et al., 1989) and modified by Szilagyi and Vorosmarty (Szilagyi and Vorosmarty, 1993). The modified model works on a grid of cells with an equal size of several kilometers each. It transforms spatially complex data on climate, vegetation, and soils into monthly predictions of soil moisture, evapotranspiration and runoff. Due to the high permeabilities of the soil as well as minor topographic relief over the re-

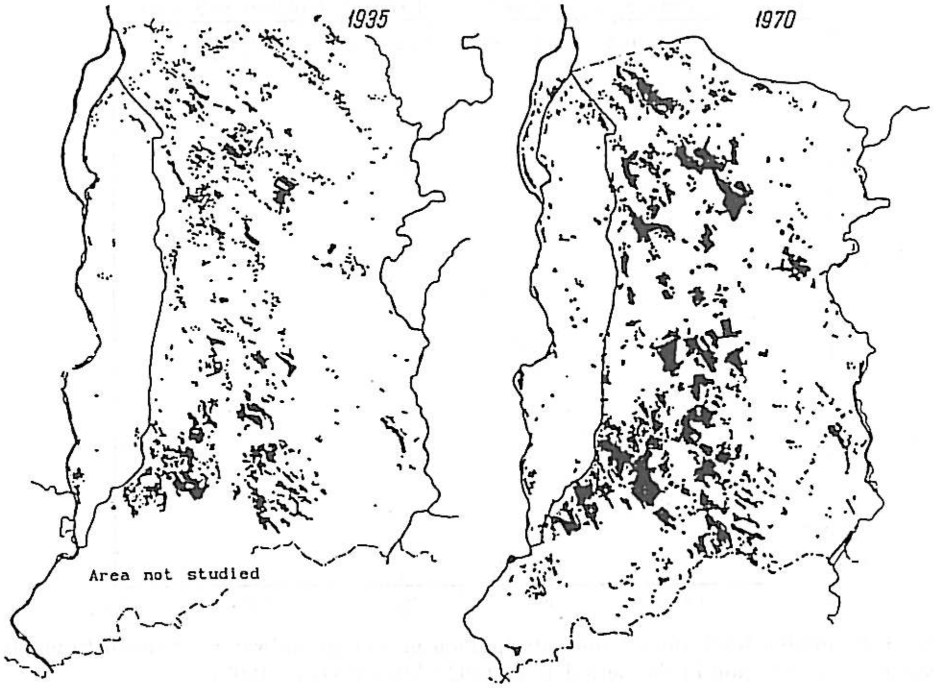

Fig. 4. Changes in the extent of forested areas during the period 1935–1970 (After Major and Neppel, 1988).
Obr. 4. Zmena lesnatosti v období rokov 1953–1970 (podľa Majora a Neppela, 1988).

gion, total runoff from each cell can effectively be treated as recharge to the unconfined aquifers in each month.

The Groundwater submodel, developed by Szilagyi and Vorosmarty (Szilagyi and Vorosmarty, 1993), driven by the monthly recharges from the WBM, predicts the mean monthly elevation of the groundwater table for each cell over time. It is based on a 2-dimensional network of the transmissivity equations constrained by open-water boundaries representing the Danube and Tisza Rivers.

The Water-Balance Model

Input data to the WBM include monthly sums of precipitation and radiation, monthly averages of temperature, vegetation cover, and soil type for each grid cell. Approximately 4000 grid cells (2.25 by 2.25 km each) cover the entire Danube—Tisza region. For every cell an independent water-balance is calculated for each month. The model makes predictions for the potential evapotranspiration (PET), evapotranspiration, soil moisture content, and runoff which is considered as recharge to the unconfined groundwater compartment in each cell. The water-accounting procedure follows the techniques developed by Thornthwaite and Mather (1957).

Soil moisture is calculated from interactions among rainfall, snowmelt recharge and PET (Vorosmarty, 1991). In the case of the Danube—Tisza region, due to its mild climate, snowcover is unimportant.

During wet months, when rain is in excess of PET, soil moisture can increase up to a maximum field capacity determined by soil texture and rooting depths. During dry months, when precipitation is exceeded by PET, soil moisture becomes a function of potential water loss. The relevant equations for soil moisture calculations applied in the model are as follows:

$$\frac{\mathrm{d}(SM)}{\mathrm{d}t} = P - PET, \qquad \text{if } P > PET,\ SM < FC, \tag{1}$$

$$\frac{\mathrm{d}(SM)}{\mathrm{d}t} = 0, \qquad \text{if } P > PET,\ SM = FC, \tag{2}$$

$$\frac{\mathrm{d}(SM)}{\mathrm{d}t} = -\alpha \cdot SM \cdot (PET - P), \qquad \text{if } P < PET, \tag{3}$$

where SM is soil moisture [mm], P – precipitation [mm month^{-1}], PET – potential evapotranspiration [mm month^{-1}], ET – estimated actual evapotranspiration [mm month^{-1}], FC – soil field capacity [mm] and α is the slope of the moisture-retention function [mm^{-1}].

PET is calculated the following way (Jensen and Haise, 1963):

$$PET = 0.016742 \cdot R \cdot (0.014 \cdot (1.8 \cdot T + 32) - 0.37), \tag{4}$$

where R is incident solar radiation [cal cm^{-1}day^{-1}], T – temperature [Celsius] and PET is potential evapotranspiration [mm day^{-1}].

The value of α can be calculated as follows:

$$\alpha = \frac{\ln(FC)}{(1.1282 \cdot FC)^{1.2756}} \tag{5}$$

which is an empirical formula for the slope of the moisture-retention function. This formula allows the retention function to behave differently for different types of soil.

Once soil moisture is determined, evapotranspiration is calculated. Following Thornthwaite and Mather, ET is set equal to PET in wet months, when the precipitation is greater or equivalent to PET. During these months it is assumed that precipitation satisfies the water demands of the vegetation. During dry months, when precipitation is less than PET, the monthly sum of ET is calculated the following way:

$$ET = PET, \qquad \text{if } P \geq PET, \tag{6}$$

$$ET = P - \frac{\mathrm{d}(SM)}{\mathrm{d}t}, \qquad \text{if } P < PET, \tag{7}$$

During wet months, when field capacity is attained and the evapotranspiration needs of the vegetation are satisfied, the surplus water seeps down into the soil to appear as groundwater recharge. This assumption may be reasonable because in the central part of the study region drainage channels are absent, changes in relief are small, and the sandy soil has high conductivity.

Before applying the model, it first had to be brought into a dynamic steady-state which was achieved by the application of the Simulated Annealing algorithm (Laarhoven and Aarts, 1987). During calibration the long-term climatic averages for each month were used. When the model reached steady state, the water-balance of the entire Danube – Tisza region could be simulated as a transient time series using the dynamic steady state for a starting point.

The Groundwater Model

Once the groundwater-recharge values are determined by the Water-Balance Model for each month at each grid cell location, groundwater dynamics can be calculated. The Groundwater Model calculates the movement of groundwater within adjacent cells using a monthly time step and a system of differential equations representing valid nodes. The basic constitutive equation is called the transmissivity equation for a two-dimensional, heterogeneous, isotropic medium (Wang and Anderson, 1982):

$$\frac{\partial}{\partial x}\left[b(x,y,t)K(x,y)\frac{\partial h(x,y,t)}{\partial x}\right] + \frac{\partial}{\partial y}\left[b(x,y,t)K(x,y)\frac{\partial h(x,y,t)}{\partial y}\right] = \\ = S(x,y)\frac{\partial h(x,y,t)}{\partial t} - R(x,y,t), \tag{8}$$

where b is the thickness of the saturated zone above the aquitard [m], K – the saturated hydraulic conductivity [m s^{-1}]; S – the storage coefficient [unitless]; R [m s^{-1}] is the recharge to groundwater calculated by the Water-Balance Model, h – the elevation of groundwater table above mean sea-level in each cell [m], and ∂x, ∂y, and ∂t are space and time derivatives, respectively.

The Crank-Nicholson implicit finite-difference scheme was used for the numerical integration of (8).

Application of the model

Data Requirements

For incident solar radiation, data measured at Budapest were applied for each cell as input to the Water-Balance Model. For monthly average temperatures and monthly precipitation there were four stations available in the study area.

River gauging stations must also be relied upon for the modeling. For the Tisza River and the Danube altogether 6 locations were chosen. By

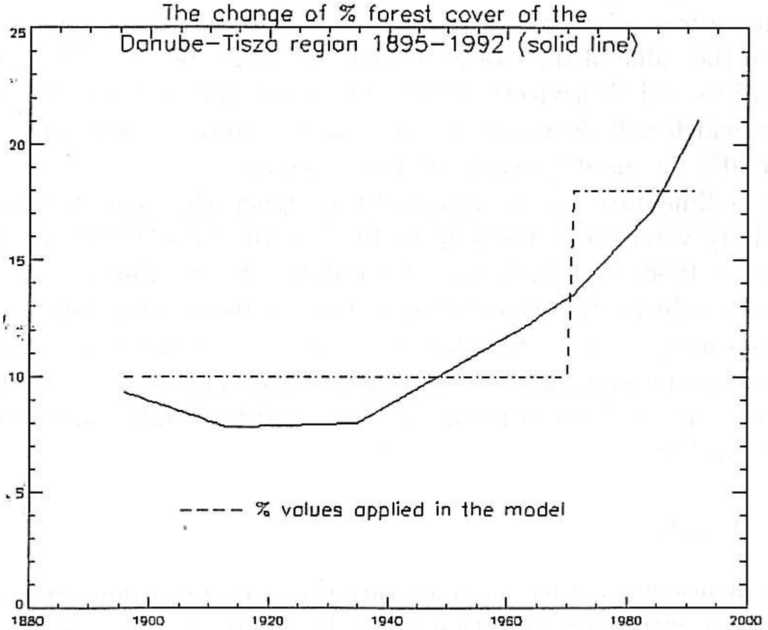

Fig. 5. The estimated forest cover in percent of the total area of the Danube—Tisza region for the period 1895–1992. The dashed line represents the values applied in the Water-Balance/Groundwater Model.

Obr. 5. Zmena lesnatosti v percentách celkovej plochy oblasti Dunaj – Tisza v rokoch 1895 —— 1992. – – – hodnoty použité v modeli.

allowing for water stage changes, the model was able to simulate a bilateral communication between the rivers and groundwater in adjacent cells.

In Fig. 5 the percentage change of forested areas in terms of the total area of the region can be seen for the period 1895 through 1992. Since 1910, the area of forests grew from 8% to 21%. In the model two levels of forest cover were applied, one low and one high. Up until 1970 an average 10% forest coverage was used which was replaced by its high level (18%) value, representing an average forest coverage for the period 1970–1992.

Some geological properties of the Danube—Tisza region are also important to consider. Measurements of thickness of the unconfined aquifer were available at approximately 70 different locations scattered more or less evenly over the entire study area. In order to assign a thickness value for each cell the two-dimensional Thiessen-polygon interpolation technique was used. After the interpolation a two-dimensional smoothing filter was applied to eliminate sharp edges between adjacent polygons. The same Thiessen-polygon technique and the filtering were applied to the following input data sets: radiation, temperature, and precipitation.

The entire region is made up mostly of fine-to-coarse sand deposits, for which the value of the storage coefficient ranges between 23% and 28% (Domenico and Schwartz, 1990). Silt lenses are scattered throughout the area which will decrease the value of the storage coefficient. Thus a value of 20% was used for each cell in the region.

For sedimentary layers typical of the region, the saturated hydraulic conductivity values may range from 10^{-8} to 10^{-3} ms^{-1}(Domenico and Schwartz, 1990) with high spatial variability. In the absence of available measured conductivities we relied upon the Simulated Annealing technique for estimating spatially distributed values of the hydraulic conductivities by the help of the observed groundwater-table elevation values (Fig. 6) for each cell. The resulting distribution of the saturated hydraulic conductivities is displayed in Fig. 7.

Model Results

As mentioned earlier, climate variations, reforestation and confined groundwater extraction were thought to be the three most important factors controlling changes in the groundwater system. According to Palfai (1992), their combined effects account for up to 85% of the magnitude of the observed groundwater decline. This assumption was tested by a step-wise set of modeling experiments.

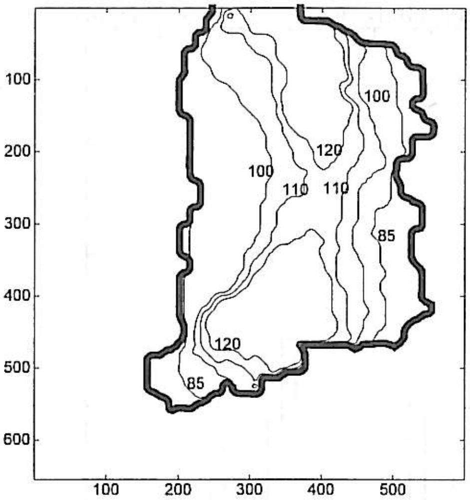

Fig. 6. Measured groundwater-table elevations [m] above mean-sea level, 1970 (After Ronai, 1961).

Obr. 6. Merané zvýšenia hladín podzemných vôd [m], vyjadrené nadmorskými výškami, 1970. (Podľa Rónaia, 1961).

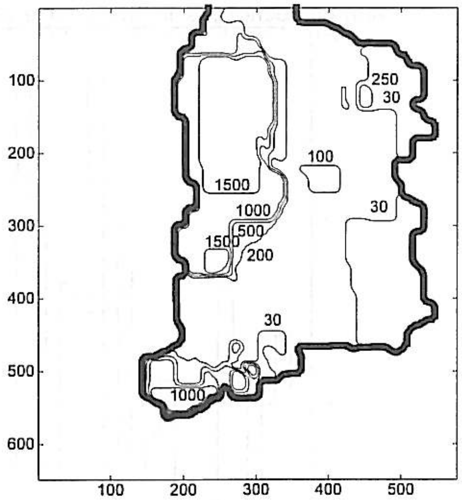

Fig. 7. The areal distribution of the optimized saturated hydraulic conductivities (10^{-6} ms^{-1}) for the Danube—Tisza region.

Obr. 7. Rozdelenie optimalizovaných hodnôt nasýtených hydraulických vodivostí [10^{-6}m s^{-1}] v danej oblasti.

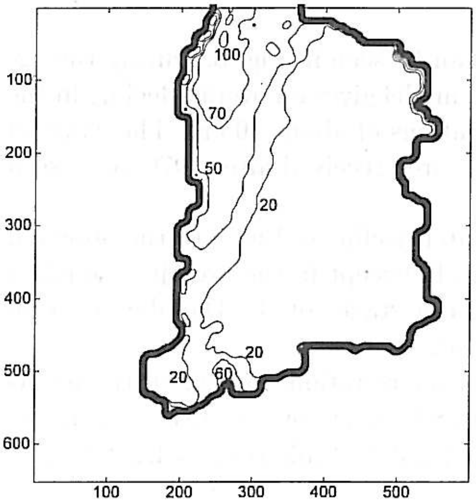

Fig. 8. The model simulated decline [cm] in groundwater levels due to observed climate variations.

Obr. 8. Modelom vypočítané zmeny úrovne hladín podzemných vôd [cm] v dôsledku zmien klímy.

First, the effect of climate variations on the groundwater system was modeled, leaving the forest cover at the relatively low level, typical of the

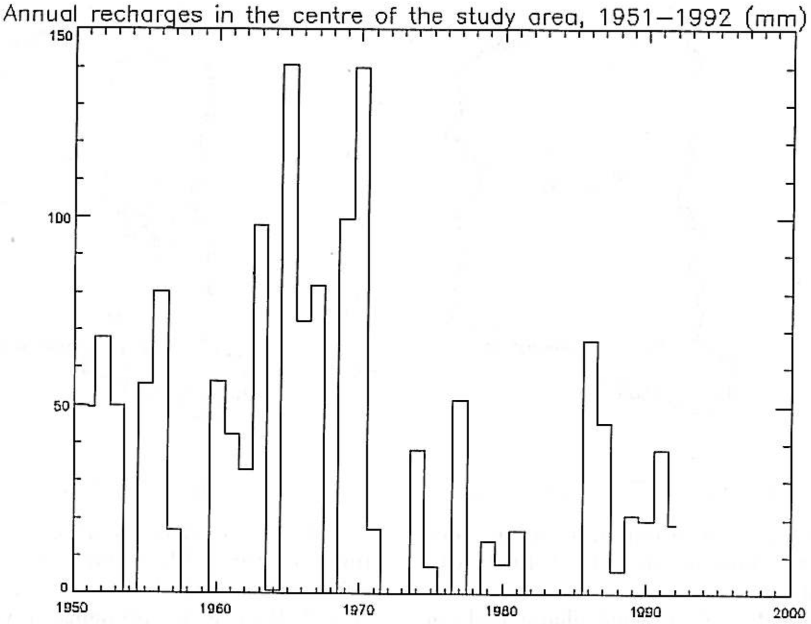

Fig. 9. Simulated annual recharges [mm] in the center of the study area, 1951–1992.
Obr. 9. Simulované ročné hodnoty doplňovania podzemných vôd [mm] v centre oblasti v rokoch 1951—1992.

1950's. The resulting model response can be seen in Fig. 8. During the 22-year period between 1971 and 1992 the model gives an overall decline in the annual average groundwater-table elevations of about 40 cm. The cause of this decline is the reduced recharge the area received after 1970, as is seen in Fig. 9.

Comparing the modeled groundwater decline in Fig. 8 to the observed decline in Fig. 1, there is no match at all, except in the area just south of Budapest where lower than average water stages of the Danube occurred over the past 22 years (Balint and Gauzer, 1994).

The next simulation step included reforestation. In Fig. 10 the model response to climate variations with an 18% forest cover is displayed. It can be seen that the reforested areas played a detectable role, at least locally, in the groundwater decline.

In the third modeling step we added a groundwater extraction component into the model. Based partly on hydro-geological model results conducted at the Hungarian Research Center for Water Resources Development (Davideszne, 1991), an annual value of 48 mm for the plateau region

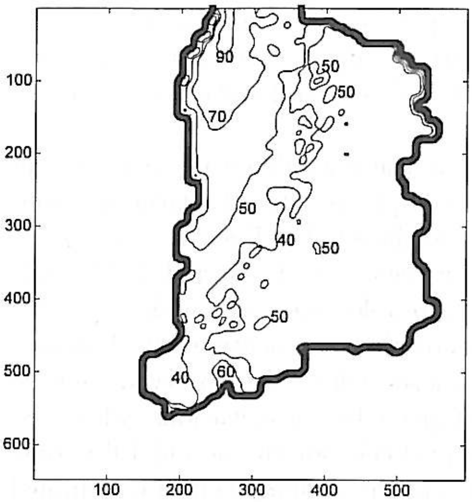

Fig. 10. The model simulated decline [cm] in groundwater levels due to the observed climatic variations and reforestation.
Obr. 10. Modelom určené zníženie hladín podzemných vôd [cm] vyvolané zalesnením a zmenami klímy.

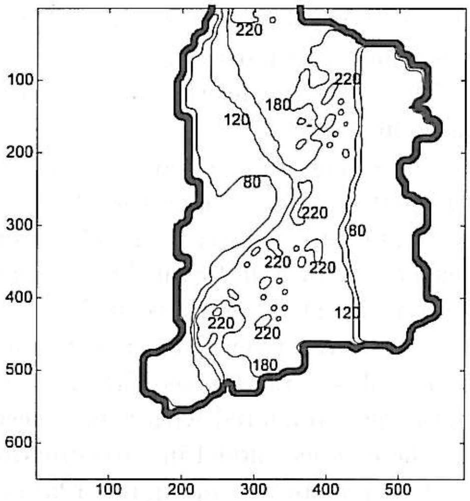

Fig. 11. The model simulated decline [cm] in groundwater levels due to the observed climatic variations, reforestation and confined groundwater extraction (including the effect of hydrocarbon mining).
Obr. 11. Modelom určené zníženie hladín podzemných vôd [cm] vyvolané zmenami klímy, zalesnením a odberom podzemných vôd (včítane banskej činnosti).

as seepage and unconfined groundwater extraction combined, was applied. Multiplying this figure with the area of the plateau region one obtains approximately 300 million m^3yr^{-1} total, as an immediate sink from the standpoint of the unconfined groundwater. Part of this unconfined groundwater loss is due to increased water pumpage (Fig. 3) from the confined aquifers and the resulting seepage from the unconfined to the confined aquifers. The resulting unconfined groundwater decline is further magnified by the effect of petroleum and natural gas production primarily from the same confined reserves. Only a small part of the reduction can be attributed to increased groundwater extractions from the unconfined aquifer itself.

Although Palfai (1992) gave petroleum and natural gas production a mere 2% weight in total groundwater reduction, the effects may be much greater. As gas is withdrawn from the sedimentary layers shared with confined groundwater reserves, pressure built up underneath the aquitard is released, giving way to increased potential seepage of groundwater from the overlying unconfined reserves. It is important to mention again that the petroleum and natural-gas production started in the late 1960's and early 1970's. That is why this sink for the unconfined groundwater could come into effect by the 1970's.

Applying an annual 48 mm sink for the unconfined groundwater in the plateau region since the 1970's on top of the climatic variations and reforestation produces a model response as depicted in Fig. 11. The decline reaches an overall 1.5 m for the plateau region in the period 1971–1992. When Fig. 11 is compared to Fig. 1, a favorable match is found.

For further verification of the model results, two locations (Kiskunmajsa and Jaszkarajeno, see Fig. 1) were chosen where the observed well-log data were compared with time series of groundwater elevations calculated by the coupled model in corresponding grid cells for the period 1951–1992 (Fig. 12). Note that in Figures 12a) and 12b) the simulated effect of confined groundwater extraction (including the effect of natural gas production) is NOT included.

Kiskunmajsa in the central plateau region belongs to a zone with a groundwater decline larger than 1 m in 1971–1992. At the same time at Jaszkarajeno the decline was much less severe in the past 22 years. While at Jaszkarajeno the observed changes can be explained by the modeled combined effects of climatic variations and reforestation, at Kiskunmajsa these mechanisms were insufficient (note the large discrepancy between measured and simulated mean monthly unconfined groundwater levels after 1970) in explaining for the large extent of unconfined groundwater decline. The observed discrepancy for the central part of the Danube – Tisza region can only be dissolved when accounting for the effects of deep groundwater pumpage and hydrocarbon mining as was demonstrated in Fig. 11.

The reason that the well-log data express higher variability than the simulated time series do is that they were measured at single points (wells), while the model gives predictions for 2.25 by 2.25 km cells, thus some smoothing is inevitable.

Summary

A coupled Water-Balance/Groundwater Model was employed for investigating the possible mechanisms resulting in an aerially and vertically unprecedented unconfined groundwater decline observed in the Danube—Tisza region in Hungary over the past 22 years. Fig. 13 displays the water-

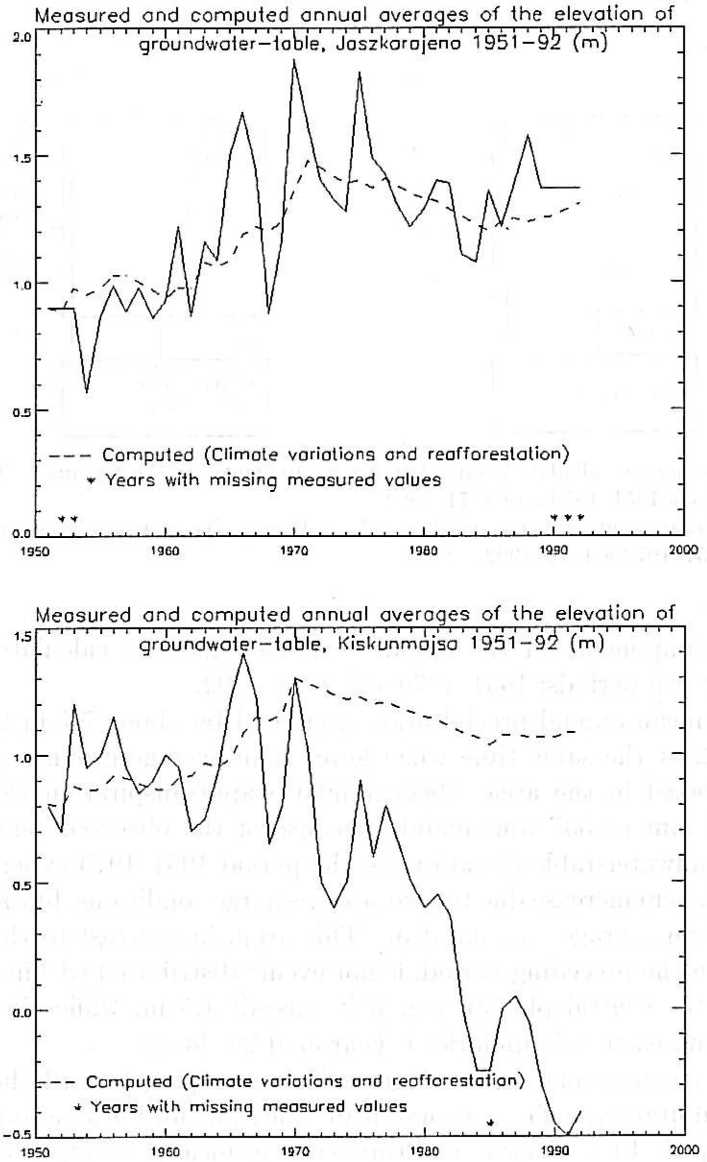

Fig. 12. Observed and simulated mean annual groundwater-table elevations ([m], above an arbitrary datum): (a) Jaszkarajeno (b) Kiskunmajsa. The simulations do not include the effect of confined groundwater extraction and hydrocarbon mining.

Obr. 12. Merané a simulované priemerné ročné zmeny polohy hladín podzemých vôd [m] nad zvolenou úrovňou: a) Jaszkarajeno, b) Kiskunmajsa. Simulácie nezahŕňajú vplyv odberu podzemných vôd a banskej činnosti, – – – simulované (zmeny klímy a zalesnenie), * roky, v ktorých chýbajú merané hodnoty.

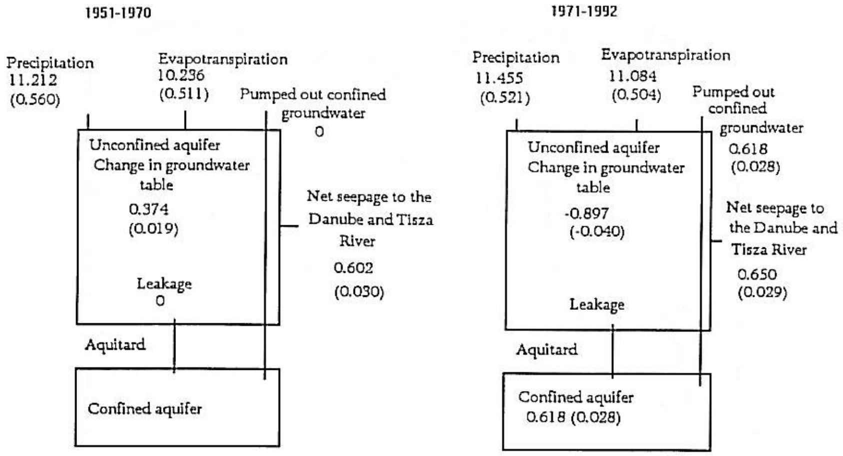

Fig. 13. The model calculated water-balance components for the Danube – Tisza region for the periods 1951–1970 and 1971–1992.
Obr. 13. Komponenty bilancie vody v oblasti Dunaj—Tisza vypočítané modelom pre obdobia 1951–1970 a 1971–1992.

balance components of the Danube—Tisza region as calculated by the model for two periods: 1951–1970 and 1971–1992.

The mean annual precipitation decreased by about 7% in the period 1971–1992 at the same time when lower than average groundwater levels were reported in the area. Mean annual evapotranspiration values grew from 511 mm to 537 mm mainly because of the observed reforestation. The groundwater-table elevations in the period 1951–1970 experienced an overall 37.4 cm increase due to favorable recharge conditions, but after 1971, displayed an average 75.2 cm drop. This drop, in contrast to the 37.4 cm increase in the preceding period, is not evenly distributed within the study area. At the central plateau region it exceeds 1.5 m, while closer to the western and eastern boundaries it is around 20–40 cm.

The mean annual value of groundwater seeping toward the Danube and its tributary, the Tisza, is practically the same for both periods. Major and Neppel (1988), based on tritium-content measurements in the 1970's, gave an estimate for this seepage, as 24 mm yr^{-1}. The 29 mm yr^{-1} value, calculated by the coupled Water-Balance/Groundwater Model matches that value.

Based on the model results the observed regional-scale unconfined groundwater decline in the period 1971–1992 can be explained by the following mechanisms with the percentage of the total change that is attributed to the particular mechanism in brackets: confined and unconfined groundwater extraction plus petroleum and natural gas production (65%), climatic variations (17%), reforestation (13%), other, not investigated sources (5%).

All these mean that without well planned and organized actions for mitigating the problem we can hardly expect the unfavorable conditions in the groundwater system of the region to change for the better. It is hoped that this study has shed light to the main factors playing a role in the region's hydrology and doing so helps provide a scientific basis for sound planning. Certainly, the present work cannot be considered as completely satisfactory in all respects, but rather as a first approach in regional-scale, physically-based, distributed-parameter modeling of the Danube – Tisza area.

Acknowledgement. The authors would like to thank Balint Gabor, Bartha Peter, Dunkel Zoltan, Gauzer Balazs, Matyasovszky Istvan, Palfai Imre, Simonffy Zoltan, Somogyvari Geza, and Szabo Gyula for their help in providing the data. Special thanks go to Fekete Balazs for his contribution in data management. This work has been supported in part by the National Aeronautics and Space Administration, Grant # 1888 and NGT 80009, as well as by the U.S.-Hungarian Joint Fund.

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Received November 29, 1996

MODELOVANIE ZNÍŽENIA HRÚBKY ZVODNE V OBLASTI MEDZI RIEKAMI DUNAJ A TISZA V MAĎARSKU

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Počas uplynulých 22 rokov bolo pozorované v oblasti Dunaj – Tisza (Maďarsko) priestorovo mimoriadne zníženie hrúbky zvodnenej vrstvy. Na vysvetlenie mechanizmov tohto javu sme použili matematický model vodnej bilancie podzemných vôd. Komponenty bilancie vody v oblasti Dunaj – Tisza boli vypočítané pre obdobia 1951–1970 a 1971–1992 (obr. 13).

Počas rokov 1971–1992, kedy sa pozorovalo zníženie hladín podzemných vôd, priemerné zrážkové úhrny sa znížili asi o 7 %. Hlavne v dôsledku zalesnenia sa zvýšili úhrny ročnej evapotranspirácie z 511 na 537 mm. V období 1951–1970 sa zvýšili hladiny podzemnej vody o 37,4 cm v dôsledku dobrých podmienok, avšak po roku 1971 sa hladiny podzemných vôd znížili v priemere o 75,2 cm. Toto zníženie v porovnaní so zvýšením o 37,4 cm v predchádzajúcom období nie je v danej oblasti rozdelené rovnomerne. V centrálnej oblasti je to 1,5 m, smerom k východným alebo západným hraniciam oblasti je zníženie asi o 20–40 cm.

Priemerný priesak podzemných vôd do Dunaja a jeho prítokov bol v obidvoch obdobiach približne rovnaký. Merania obsahu trícia (Major, Neppel, 1988) v roku 1970 viedli k hodnote 24 mm/rok. Výsledok získaný navrhnutým modelom – 29 mm/rok, potvrdzuje túto hodnotu.

Výsledky modelovania zníženia hrúbky zvodnenej vrstvy sú: odber podzemnej vody a ťažba ropy a plynu (65 %), zmeny klímy (17 %), zalesnenie (13 %) a iné, neštudované príčiny (5 %).

Z uvedeného vyplýva, že bez koordinovaných činností nemožno očakávať zlepšenie podmienok systému podzemných vôd. Veríme, že táto štúdia pomôže skoncentrovať pozornosť na zníženia hladín podzemných vôd.

Výsledky uvedené v tejto štúdii nemôžu byť považované za všestranne uspokojivé, sú skôr prvým pokusom o riešenie tohto problému matematickým modelovaním v oblasti Dunaj – Tisza.

Zoznam použitých symbolov

SM – obsah vody [mm],
P – zrážky [mm mes^{-1}],
PET – potenciálna evapotranspirácia [mm mes^{-1}],
ET – aktuálna evapotranspirácia [mm mes^{-1}],
FC – poľná vodná kapacita [mm],
α – súčiniteľ v rov. (3),
R – intenzita slnečného žiarenia v rov. (4) [cal cm^{-1} d^{-1}],
T – teplota vzduchu [°C],
b – hrúbka vodou nasýtenej zóny nad nepriepustnou vrstvou [m],
K – hydraulická vodivosť vodou nasýtenej zeminy [m s^{-1}],
R – intenzita doplňovania podzemných vôd v modeli [m s^{-1}],
h – zvýšenie hladiny podzemnej vody nad úrovňou mora v každom uzle [m].