DOI: 10.21120/LE/10/3-4/7 **Landscape & Environment 10 (3-4) 2016. 145-152**

GEOINFORMATIC BACKGROUND OF GEOTHERMAL ENERGY UTILISATION AND ITS APPLICATIONS IN EAST HUNGARY

TAMÁS BUDAY* − ERIKA BUDAY-BÓDI − RICHARD WILLIAM MCINTOSH − MIKLÓS KOZÁK

University of Debrecen, Department of Mineralogy and Geology,
H-4032 Debrecen, Egyetem tér 1., Hungary
*e-mail: buday.tamas@science.unideb.hu

Received 29 July 2016, accepted in revised form 9 September 2016

Abstract
Powerful geothermal energy utilisation requires geoinformatic tools from potential surveying through the designing and setting of geothermal systems to certain operational tasks. However, practical data processing strongly depends on the elaboration of basic data and information, the type of the geothermal energy harvesting system and the character of the calculation demonstrated by case studies from East Hungary, in addition the usability of the resulted maps are also presented. Besides their usability for investors these maps could be refined in the location of the development before hydraulic/heat transport modelling.

Keywords: geothermal, geoinformatics, ground coupled heat pump, Debrecen

1. Introduction

Geothermal energy utilisation is an increasingly hot issue as the share of renewable energy resources in energy production increases, the environmental effects of energy production are reduced and the energy network is decentralised. In order to improve geothermal energy utilisation regional reports have been composed (e.g. Hurter – Haenel 1992; Rezessy et al. 2005; Kovács 2010; Kozák et al. 2011; Bertermann et al. 2013; Nádor et al. 2013) studying either the conditions or utilisation demands or both. Partly independent from the size of the studied area such reports require the composition of geoinformatic databases related to the surface and subsurface data of the area and also the completion of geoinformatic measures in such databases (Noorollahi et al. 2008; Bertermann et al. 2013).

Geoinformatic databases and measures may range from simple ones to complex ones depending on the aims of the report. Further important parameters are the vertical and horizontal resolution of data that determine the scale of the obtained data and thus the scale of applicability as well.

Besides regional reports presenting general possibilities settlement level analyses can be prepared (e.g. Mádl-Szőnyi et al. 2015; Buday 2016) that via the accurate outlining of conditions and demand on maps may help the selection of optimal locations for installation or in the case of shallow geothermal systems may identify areas not suitable for utilisation. Due to the distribution of data, field data acquisition will always remain necessary when particular systems are planned.

Geothermal energy is defined here as the excess heat of the subsurface space. This quantity of heat in a space of homogeneous material and temperature can be calculated as follows (Muffler – Cataldi 1978):

$$E_b = \left[\phi c_f \rho_f + (1-\phi) c_m \rho_m\right](T_r - T_0)V$$

where: E_b – inner energy [J]; ϕ – porosity [–]; c_f – specific heat of the fluid [J/(kg·K)]; ρ_f – density of the fluid [kg/m^3]; c_m – specific heat of the rock matrix [J/(kg·K)]; ρ_m – density of the rock matrix [kg/m^3]; T_r – reservoir temperature [K]; T_0 – average temperature at the surface[K].

In the case of a given area or reservoir the resolution of available data determine the unit of volume in which homogeneity can be assumed. Dividing the reservoir by this unit the results can be summed up.

Results obtained in this way, however, yield no information regarding exploitability, expected maximum performance, sustainable discharge, but represent a theoretical potential. Exploitable potential in contrast is influenced by the chosen technology, economic environment, legal regulations and several other factors the majority of which could be studied using geoinformatic methods.

2. Basic geothermal applications of geoinformatics

Calculating the theoretical geothermal potential using the formula presented in the previous chapter raises numerous geoinformatic questions and tasks. Distribution of data points is not even either horizontally or vertically, the space is not homogeneous, neither isotropic and even breaks may be present in the surfaces thus interpolation and finding averages may become erroneous. In the case of few data, validating the obtained results is limited and uncertainties have to be tackled (Rezessy et al. 2005; Sanyal – Morrow 2010; Procesi – Poncia 2013).

It is important to handle the elements of the subsurface space as both wireframes and 3D blocks. Both interpretations require spatial interpolation based on the measured data (points, along a line or surface). Mapping and placing faults that break continuity into models may present a significant geoinformatic challenge.

Another important aspect is the geothermal interpretation and international harmonization of various reserves estximation methods (Rybach 2010; Nádor 2016). For this the modifying factors have to be identified that could be used for making the definition of potential more-and-more accurate (theoretical – technical – economic – sustainable – exploitable, Rybach 2010).

Exploitability is generally determined via numerical modelling. For this the location of bordering surfaces and the distribution of parameters important hydrodynamically and thermodynamically have to be handled (Kohl et al. 2003; Fujii et al. 2007).

At less explored areas the localisation of potential reservoirs and exploration wells is based on the geoinformatic study of the presence and distribution of indicators characteristic for the type of the reservoir. If the reservoir is well-explored these deep technologies are less sensitive to conditions at the surface because it is not necessary to drill the wells at the surface plot of the reservoir due to the fact that inclined wells can be drilled thus smaller built-up, protected or otherwise limited areas can be avoided.

When systems with borehole heat exchangers (BHEs) are installed such drilling is either not possible or would make the investment too costly. Therefore the role of near-surface conditions is increasingly significant in the case of BHEs and near-surface systems (collectors and energy piles), thus GIS databases of surface data become more valuable and important.

Planning surface and near surface instalments for geothermal energy usage may require significant geoinformatic analyses with which the hydraulics or cost efficiency of the systems could be optimised. For example in the case of Létavértes, near Debrecen the accurate location of the buildings to be involved in geothermal energy utilisation was identified while the characteristics (attributes) of the buildings included parameters like heating and/or cooling energy demand and photos (Husi et al. 2012).

3. Case studies

Thermal water reservoirs of Hortobágy-Hajdúság-Nyírség area

Regional thermal reservoir exploration is in progress based on seismic and well-log data in the area of Hortobágy, Hajdúság and West Nyírség (Fig. 1, Bódi et al. 2014, 2015). The potential reservoir covers the clastic sediments deposited in the Pannonian stage (Juhász 1992; Magyar 2010). 3D solid model was built from 1D and 2D lithostratigraphic and sequence stratigraphic data based boundary surfaces, then along a rectangular grid the depths of boundary surfaces were determined. Between the determined values arithmetic operations could be performed, thus the thickness of the Pannonian s.l. sediments, the average temperature and energy density of the reservoir were calculated (Fig. 1). This method is an approximation, more detailed analysis would require the configuration of 3D blocks and the determination of parameter values and energy density in each block.

Calculated results show significant diversity in the theoretical geothermal potential of the Pannonian reservoirs inside a relatively small area. Diversity is lower in the northeast part of the area, where the

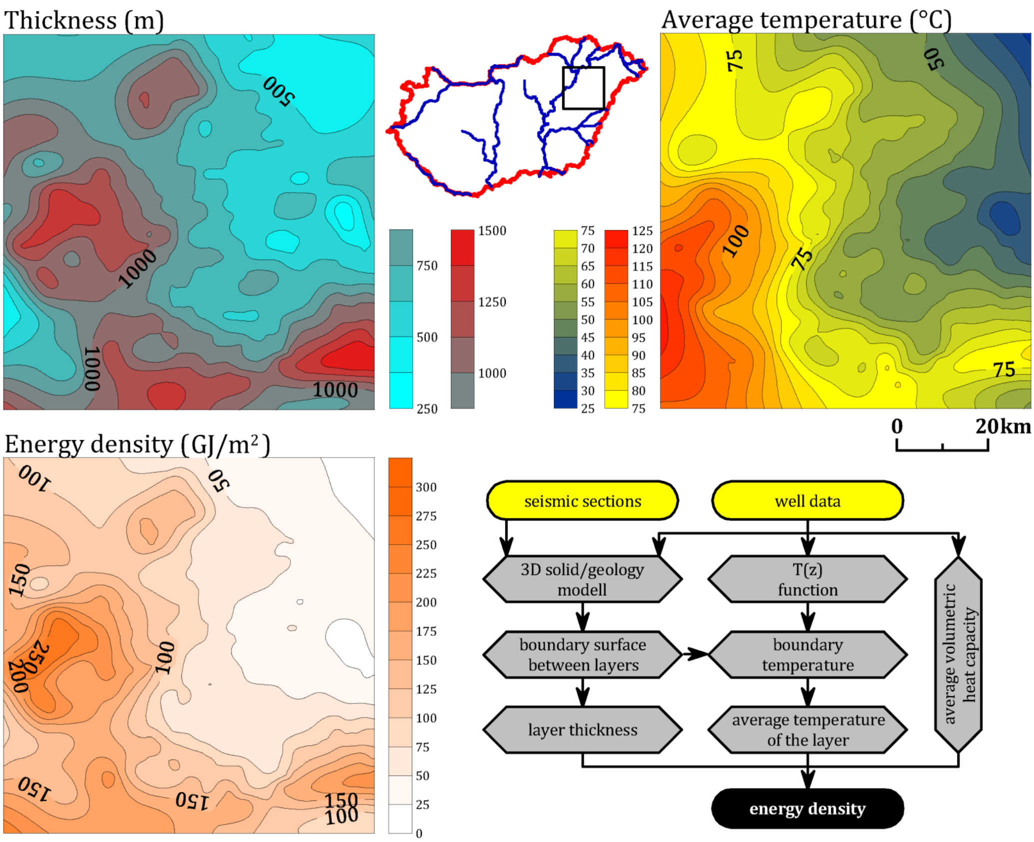

Fig. 1. Calculation of the theoretical geothermal potential of the Pannonian reservoirs in Hortobágy–Hajdúhát–West-Nyírség study area (base maps, flow diagram and result map)

thickness of the Miocene volcanic rocks is higher (Széky-Fux et al. 2007) and the theoretical geothermal potential is lower. On the other part of the area, where faults influence the structure of the reservoirs, diversity is higher (Bódi et al. 2015).

Natural background of the installability of heat pump systems

Heat pumps exploit the ambient energy of the air, surface water, groundwater or soils, deposits and rocks. Certain types could be installed anywhere independent from natural conditions, however, the operation parameters of heat pumps and thus the thrift of the system depend on the configuration of the source loop.

In the case of geothermal heat pumps with closed source loop the thrift and the size of the source loop primarily depends on the thermal conductivity of the penetrated medium, i.e. mineral composition, porosity, water content (Bertermann et al. 2013), but these parameters are not informative enough for an investor or decision-maker.

The installability map shown below (Fig. 2) is suitable for these purposes, combining the information content of a geologic map with the scale of 1:100000 (Gyalog – Síkhegyi 2005), average groundwater table depth map with the scale of 1:200000 (Rónai 1961) and a map of nature protection and NATURA 2000 areas available from the Nature Conservation Information System.

5+1 classes are formed from datasets of each layer considering installability of ground coupled loop: not suggested; unfavourable; neutral; favourable; very favourable and

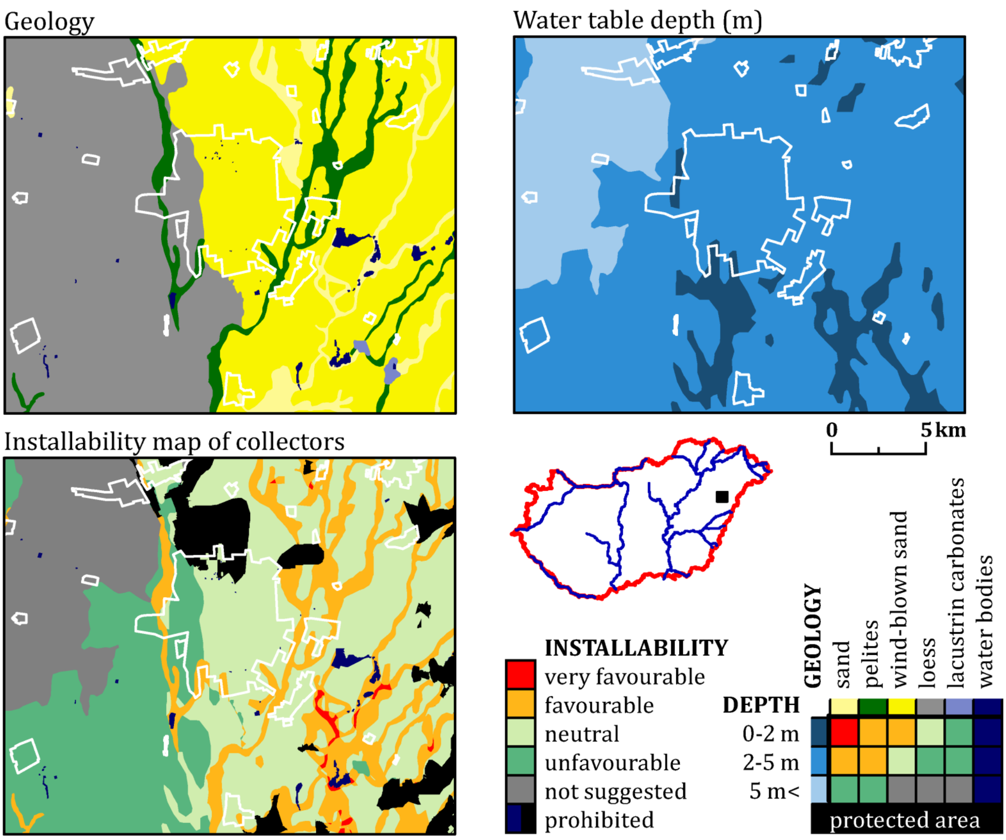

Fig. 2. Developing the installability map of horizontal collectors around Debrecen (base maps, possible classification and result map)

prohibited. Joint interpretation of the layers in the case of few layers could become with the re-classification of all evolving variations (as in Fig. 2.) or in the case of numerous layers with the (weighted) variation of the classes.

Both databases represent only the shallowest (<10 m) geological strata, thus the presented installability map can be used primarily with systems with horizontal collectors. Based on this, for the installation of horizontal systems natural conditions are favourable in the eastern part of Debrecen, in the area of the former river valleys. Collector systems require relatively large areas (even several hundred m^2), thus the application of further layers based features could be necessary. However, from these features geoinformatic databases have limited access or do not exist yet and there preparation requires specialized knowledge.

Due to the character of the study area potential further layers could be geomorphological or landscape stability maps, or at least information at microregional landscape level. The previous maps are answering the questions about the necessary extent of landscaping during installation of the collectors (thus cost questions), and how the landscape affects the systems. The latter maps give information about potential landscape degradation caused by the installation (e.g. increased erosion or deflation, Lóki 2003; Lóki – Négyesi 2009). Large(r) scale maps of water level depth or studying the changes of the water level depth could be other significant information (in the sample area e.g. Csordás – Lóki 1989; Négyesi 2010), since permanent depression of water level can make the operation of the systems impossible with collectors. Based on these modifying factors, installation of collectors is realistic in unbuilt areas in the eastern part of Debrecen where landscaping has already taken place.

Application of these analyses and results to determine the location of vertical borehole heat exchangers could be limited, since the ground is not homogeneous even in the upper 100 m. In the fluvial sequences, that are typical in the area the depth and thickness of sand and clay bodies are spatially rather different (Rónai 1985; Demeter et al. 2010; Lóki 2010, 2012; Lóki et al. 2014). Thus in some areas the shorter and more pieces of BHEs, while in other areas the longer and lesser pieces of BHEs are favourable due to the higher heat egress of the layers situated deeper.

Effects of the built environment on the installability of geothermal heat pump systems

Installability of geothermal heat pump systems is influenced by not only the natural conditions but the extant architectural, infrastructural, economic and other facilities as well. Due to the high area demand of collectors primarily BHEs or energy piles could be installed in built-up areas of settlements. For sustainability purposes the minimal distance between the boreholes is 5–7 m, thus the size and shape of the lot is very important, especially if more than one borehole is needed.

In certain parts of Debrecen installability research of BHEs was performed (Buday 2016). Its result shows that space is not enough for BHE installation to serve the whole heating and cooling energy demand in areas with continuous row of buildings especially in the city.

In contrast, in the suburbs with semi-detached/detached houses or in garden plots around Debrecen enough space is available for energy harvesting. Size and rate of these potential areas are decreased by the place of the buildings, the infrastructural features and their protection zones in addition the archeologic and water source protection areas. For example in Hungary the drilling activity needed for installing BHEs could be prohibited if the installation or the operation could endanger water quality (Government Decree No. 123/1997). In the case of Debrecen Waterworks I., II. and IV. water source protecting areas have been determined, thus potential areas for BHE installation are limited the south part of the town (Fig. 3).

Built environment has other effects on the installation of the systems. In towns both air temperature and subsurface temperature are higher than the temperature of the rural areas around towns. This phenomenon means higher theoretical geothermal potential (Allen et al. 2003; Zhu et al. 2010; Arola – Korkka-Niemi 2014), in addition lower heating energy demand. In Debrecen extra heat content both above and under the surface is proved (e.g. Szegedi et al. 2014, Buday 2015), but its effect on the renewable energy potential has not been assessed quantitatively yet partly due to incomplete geoinformatic methods.

Complex usage of renewable energy sources is based on the joint survey of theoretical, technical and sustainable potentials. Due to the heat aim and availability of the source the main joint sources could be solar and geothermal energy. In solar energy surveys the part of roofs where solar collectors or photovoltaic panels could be installed economically could be determined using various geoinformatic methods (e.g. Santos et al. 2014; Szabó et al.

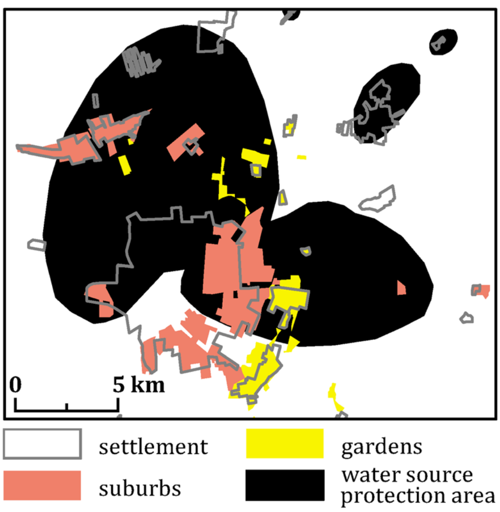

Fig. 3. Relative position of water source areas, suburbs and garden plots around Debrecen

2015; Szabó et al. 2016; Horváth et al. 2016). Based on their results the real extent of the buildings, in some cases the covered parts or planted areas with trees or scrubs of the lot could be determined. Consequently these data combined with cadastral maps are appropriate to identify the areas available for geothermal energy applications as well (Buday 2016). Installation of solar and geothermal systems together serve further possibilities in underground storage of the extra summer heat (Nordell – Hellström 2000) – which is demonstrated in Debrecen as well (Buday – Török 2011; Buday 2015) – making this systems energy and cost-effective.

4. Conclusions

Detailed studies of the utilisation of geothermal energy require geoinformatic databases. These, however, contain real 3D data the distribution and reliability of which are limited compared to the availability of surface data, however reliability and time dependent changes of the subsurface data are less controllable. Despite this, installation studies, hydrodynamic and heat transport models yield factual energetic data thus their role in the spreading of renewable energy resources is essential.

Due to their common geoinformatic bases and cost effectiveness it is sensible to perform surveys aiming to analyse each renewable energy resource together.

5. References

Allen, A. – Milenic, D. – Sikora, P. (2003): Shallow gravel aquifers and the urban 'heat island' effect: a source of low enthalpy geothermal energy. Geothermics. 32(4-6): 569-578.

Arola, T. – Korkka-Niemi, K. (2014): The effect of urban heat islands on geothermal potential: examples from Quaternary aquifers in Finland. Hydrogeology Journal. 22(8): 1953-1967.

Bertermann, D. – Bialas, Ch. – Morper-Busch, L. – Klug, H. – Rohn, J. – Stollhofen, H. – Psyk, M. – Jaudin, F. – Maragna, Ch. – Einarsson, G.M. – Vikingsson, S. – Orosz, L. – Jordan, Gy. – Vîjdea, A-M. – Lewis, M. – Lawley, R.S. – Latham, A. – Declercq, P-Y. – Petitclerc, E. – Zacherl, A. – Arvanitis, A.A. – Stefouli, M. (2013): ThermoMap - An Open-Source Web Mapping Application for Illustrating the very Shallow Geothermal Potential in Europe and selected Case Study Areas. In: European Geothermal Congress. Pisa 3-7 June 2013, Proceedings, SG3-05, 8.

Bódi, E. – Buday, T. – McIntosh R.W. (2014): Consequences of tectonic events on porous thermal water reservoirs, NE Hungary. In: 5th European Geothermal PhD Day, 31.03-02.04.2014, Darmstadt, Abstracts, Technische Universitäte Darmstadt, Darmstadt, 14-15.

Bódi, E. – Buday, T. – Kovács, R.L. – McIntosh, R.W. (2015): Sequence stratigraphic based modeling and geothermal potential estimation in the case of Neogene thermal water reservoirs, central Trans Tisza Region, Hungary. In: 6th Geothermal PhD Day, Delft, The Netherlands, 25-27 February 2015, Proceedings, 19-20.

Buday, T. (2015): A felső kéregbeli hőterjedés modellezése és alkalmazási lehetőségei Kelet-Magyarországon. Manuscript, PhD Dissertation, University of Debrecen, Debrecen, 130. (in Hungarian)

Buday, T. (2016): Geotermikus hőszivattyús rendszerek primeroldali kiépíthetőségének térinformatikai vizsgálata városi területeken. In: Balázs, B. (Ed.)(2016): Az elmélet és a gyakorlat találkozása a térinformatikában VII.: Térinformatikai Konferencia és Szakkiállítás. Debrecen, 25.05.2016.-26.05.2012. Debreceni Egyetemi Kiadó, Debrecen, 107-114. (in Hungarian)

Buday, T. – Török, I. (2011): Működő hőszivattyús rendszerek hatása a felszínközeli üledékek hőmérsékletére egy Debreceni példa alapján. Magyar Épületgépészet. 59(1-2): 21-24. (in Hungarian)

Csordás, L. – Lóki, J. (1989): A talajvízszint változásának vizsgálata a Nagykunságban és a Hajdúságban. Alföldi tanulmányok, 13: 47-62. (in Hungarian)

Demeter, G. – Püspöki, Z. – Lazányi, J. – Buday T. (2010): Szekvencia-sztratigráfiai alapú földtani kutatás Nyíregyháza-Szatmárnémeti térségében. Dominium Könyvkiadó, Debrecen. 287. (in Hungarian)

Fujii, H. – Inatomi, T. – Itoi, R. – Uchida, Y. (2007): Development of suitability maps for ground-coupled heat pump systems using groundwater and heat transport models. Geothermics. 36(5): 459-472.

Gyalog, L. – Síkhegyi, F. (2005): Magyarország földtani térképe, M=1:100 000. A Magyar Állami Földtani Intézet kiadványa, Budapest.

Horváth, M. – Kassai-Szoó, D. – Csoknyai, T. (2016): Solar energy potential of roofs on urban level based on building typology. Energy and Buildings. 111: 278-289.

Hurter, S., Haenel, R. (2002): Atlas of geothermal resources in Europe. Office for Official Publications of the European Communities, Luxemburg, 91.

Husi, G. – Kiss Bacsó, L. – Lóki, J. (2012): Geotermikus energia hasznosítási lehetőségének térinformatikai feldolgozása Létavértes környékén. In: Lóki. J. (Ed.)(2012): Az elmélet és gyakorlat találkozása a térinformatikában: III. Térinformatikai konferencia és szakkiállítás. Debrecen, 24.05.2012.-25.05.2012. Debreceni Egyetemi Kiadó, Debrecen. 169-174. (in Hungarian)

Juhász, Gy. (1992): A pannóniai s.l. formációk térképezése az Alföldön: elterjedés, fácies és üledékes környezet. Földtani Közlöny. 122(2-4): 133-165. (in Hungarian)

Kohl, Th. – Andenmatten, N. – Rybach, L. (2003): Geothermal resource mapping—example from northern Switzerland. Geothermics. 32(2-4): 721-732.

Kovács, B. (2010): Szabolcs-Szatmár-Bereg és Szatmár megyék geotermikus atlasza. Kézirat, Miskolc. 27+35. (in Hungarian)

Kozák, M. – McIntosh, R. W. – Buday, T. (2011): Geotermikus rendszerek fenntarthatóságának integrált modellezése. 3. munkacsoport. Hidrogeotermikus rendszerek és földtani vetületeik. – Debreceni Egyetem, Debrecen. 140 p. (in Hungarian)

Lóki, J. (2003): A szélerózió mechanizmusa és magyarországi hatásai. MTA doktori értekezés. Kézirat. 265. (in Hungarian)

Lóki, J. (2010): Lepelhomok vizsgálatok a Nyírség és a Hajdúhát határán. In: Lóki, J. (Ed.) (2010): Interdiszciplinaritás a természet- és társadalomtudományokban: tiszteletkötet Szabó József geográfus professzor 70. születésnapjára. Debreceni Egyetem Természetföldrajzi és Geoinformatikai Tanszék, Debrecen, 209-217. (in Hungarian)

Lóki, J. (2012): A nyírségi futóhomokformák átalakulása –antropogén és klímatikus hatások. In: Nyári D. (Ed.)(2012): Kockázat – konfliktus – kihívás. Szegedi Tudományegyetem Természeti Földrajzi és Geoinformatikai Tanszék, Szeged, 549-564. (in Hungarian)

Lóki, J. – Négyesi, G. (2009): A széleróziós információs rendszer alapjai. In: Hegedűs A. (Ed.)(2009): Geoinformatika és domborzatmodellezés 2009: A HunDEM 2009 és a GeoInfo 2009 konferencia és kerekasztal válogatott tanulmányai. Miskolc, 24.04.2009-25.04.2009. Miskolci Egyetem, Miskolc, Paper 7, 13. (in Hungarian)

Lóki, J. – Szabó, J. – Szabó, G. (2014): Újabb adatok a Hajdúhát (Hajdúság) negyedidőszaki fejlődéstörténetéhez. Földrajzi Közlemények. 138(1): 37-49. (in Hungarian)

Mádl-Szőnyi, J. – Virág, M. – Zsemle, F. (2015): Potential maps for the hydrogeologic prerequisites of the installation of deep geothermal doublets and groundwater source heat pump systems in Budapest, Hungary. Central European Geology. 58(1-2): 114-128.

Magyar, I. (2010): A Pannon-medence ősföldrajza és környezeti viszonyai a késő miocénben. Geolitera, Szeged. 140. (in Hungarian)

Muffler, P. – Cataldi, R. (1978): Methods for regional assessment of geothermal resources. Geothermics. 7(2-4): 53-89.

Nádor, A. – Zilahi-Sebess, L. – Szeiler, R. – Simó, B. – Hofmeister, M. – Dumas, Ph. (2013): Matching geothermal potential and heat demand of Europe: the web-map tool of the Geo-DH project to promote geothermal district heating. In: European Geothermal Congress. Pisa 3-7 June 2013, Proceedings, HS1-17, 8 p.

Nádor, A. (2016): A geotermikus energiavagyon osztályozási és jelentési rendszerei és a hazai adaptáció első lépései. Földtani Közlöny. 146(2): 123-134. (in Hungarian)

Négyesi, G. (2010): A talajvízállás vizsgálata a Hajdúságban. – In: Interdiszciplinaritás a természet- és társadalomtudományokban: tiszteletkötet Szabó József geográfus professzor 70. születésnapjára. Debreceni Egyetem Természetföldrajzi és Geoinformatikai Tanszék, Debrecen. 243-250. (in Hungarian)

Noorollahi, Y. – Itoi, R. – Fujii, H. – Tanaka, T. (2008): GIS integration model for geothermal exploration and well siting. Geothermics. 37(2): 107-131.

Nordell, B. – Hellström, G. (2000): High temperature solar heated seasonal storage system for low temperature heating of buildings. Solar Energy. 69(6): 511-523.

Procesi, M. – Poncia, P (2013): Mapping of the shallow geothermal resource and potential direct uses for the northern province of Rome (Central Italy). The Fuzzy Logic a useful analysis tool. In: European Geothermal Congress. Pisa 3-7 June 2013, Proceedings, HS1-69, 10.

Rezessy, G. – Szanyi, J. – Hámor, T. (2005): Jelentés a geotermikus energia állami nyilvántartásáról, I. fázis. Manuscript, Hungarian Geological Survey, 85. (in Hungarian)

Rónai, A. (1961): Az Alföld talajvíztérképe: magyarázó a talajvíztükör felszín alatti mélységének 1:200000-es méretű térképéhez. MÁFI, Budapest. 102. (in Hungarian)

Rónai, A. (1985): Az Alföld negyedidőszaki földtana. – Geologica Hungarica Series Geologica. 21. MÁFI, Budapest. 446. (in Hungarian)

Rybach, L. (2015): Classification of geothermal resources by potential. Geothermal Energy. Science 3: 13-17.

Santos, T. – Gomes, N. – Freire, S. –Brito, M.C. – Santos, L. – Tenedório, J.A. (2014): Applications of solar mapping in the urban environment. Applied Geography. 51: 48-57.

Sanyal, S.K. – Morrow J.W. (2010): Quantification of Geothermal Resource Risk – A Practical Perspective. GRC Transactions. 34: 125-130.

Szabó, G. – Enyedi, P. – Szabó, Gy. – Fazekas, I. – Buday, T. – Kerényi, A. – Paládi, M. – Mecser, N. – Szabó, Sz. (2015): Preliminary results on the determination of solar energy potential using LiDAR technology. International Review of Applied Sciences and Engineering. 6(1): 11-17.

Szabó, Sz. – Enyedi, P. – Horváth, M. – Kovács, Z. – Burai, P. – Csoknyai, T. – Szabó, G. (2016): Automated registration of potential locations for solar energy production with Light Detection And Ranging (LiDAR) and small format photogrammetry. Journal of Cleaner Production. 112(5): 3820-3829.

Szegedi, S. – Tóth, T. – Lázár, I. (2014): Role of urban morphology in development of the thermal excess in the city of Debrecen, Hungary. Environmental Engineering and Management Journal. 13(11): 2805-2808.

Széky-Fux, V. – Kozák, M. – Püspöki, Z. (2007): Covered Neogene magmatism in eastern Hungary. ACTA GGM DEBRECINA Geology, Geomorphology, Physical Geography Series. 2: 79-104.

Zilahi-Sebess L., Merényi, L., Paszera, Gy., Tóth, Gy., Boda, E., Budai, T. (2012): Nyersanyag készletek, A hazai ásványi nyersanyagpotenciál, 5. Geotermikus energia, (Háttértanulmány), Nemzeti Energiastratégia, Készletgazdálkodási és hasznosítási cselekvési terv, Kézirat, 84 p (in Hungarian)

Zhu, K. – Blum, Ph. – Ferguson, G. – Balke, K-D. – Bayer, P. (2010): The geothermal potential of urban heat islands. Environmental Research Letters. 5: 044002 1-6.