Hydrogeology of the Pannonian Basin

István Almási and János Szanyi

THE GROUNDWATER PROJECT

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The Groundwater Project

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The Groundwater Project Foreword

The United Nations (UN) - Water Summit on Groundwater held from 7 to 8 December 2022 at the UNESCO headquarters in Paris, France, concluded with a call for governments and other stakeholders to scale up their efforts to better manage groundwater. The intent of the call to action was to inform relevant discussions at the UN 2023 Water Conference held from 22 to 24 March 2023 at the UN headquarters in New York City. One of the required actions is *strengthening human and institutional capacity*, for which groundwater education is fundamental.

The 2024 World Water Day theme is *Water for Peace*, which focuses on the critical role water plays in the stability and prosperity of the world. The UN-Water website↗ states that *more than three billion people worldwide depend on water that crosses national borders*. There are 592 transboundary aquifers, yet most countries do not have an intergovernmental cooperation agreement in place for sharing and managing the aquifer. Moreover, while groundwater plays a key role in global stability and prosperity, it also makes up 99 percent of all liquid freshwater—accordingly, groundwater is at the heart of the freshwater crisis. *Groundwater is an invaluable resource*.

The Groundwater Project (GW-Project), a registered Canadian charity founded in 2018, is committed to advancement of groundwater education as a means to accelerate action related to our essential groundwater resources. We are dedicated to *making groundwater understandable* and, thus, enable *building the human capacity for sustainable development and management of groundwater.* To that end, the GW-Project creates and publishes high-quality books about *all-things-groundwater*, for all who want to learn about groundwater. Our books are unique. They synthesize knowledge, are rigorously peer reviewed and translated into many languages, and are free of charge. An important tenet of GW-Project books is a strong emphasis on visualization: Clear illustrations stimulate spatial and critical thinking. The GW-Project started publishing books in August 2020; by the end of 2023, we had published 44 original books and 58 translations. The books can be downloaded at gw-project.org↗.

The GW-Project embodies a new type of global educational endeavor made possible by the contributions of a dedicated international group of volunteer professionals from a broad range of disciplines. Academics, practitioners, and retirees contribute by writing and/or reviewing books aimed at diverse levels of readers including children, teenagers, undergraduate and graduate students, professionals in groundwater fields, and the general public. More than 1,000 dedicated volunteers from 70 countries and six continents are involved—and participation is growing. Revised editions of the books are published from time to time. Readers are invited to propose revisions.

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The GW-Project Board of Directors, January 2024

Foreword

The Pannonian Basin aquifer system is especially important because it provides groundwater to nine eastern European countries centered around Hungary, the country on which this book is focused. Groundwater has been important in this region since Roman times two millennia ago and groundwater currently provides most of the drinking water to the 9.6 million Hungarian citizens.

Hydrogeology of the Pannonian Basin describes groundwater occurrence, flow, uses, and the broader relevance of groundwater in one of the largest and most complex aquifer systems in the world. However, this aquifer system is important in Hungary for reasons that extend much beyond drinking water including irrigation, industrial uses, geothermal energy, tourism associated with the abundant mineral springs and hot springs, and its role in the formation of petroleum accumulations that occur at exceptionally shallow depth.

Groundwater has played an influential role in the history of this part of Europe where, beginning in the mid-1800s, much expanded groundwater use emerged as a result of technological advancement in drilling deep wells and modern groundwater governance. In prior centuries, the fundamental nature of the Hungarian lowlands was altered by extensive drainage works that converted vast wetlands and shallow lakes into agricultural land. This enabled the population of Hungary to expand and become an important European country.

The particular features of Hungarian hydrogeology played an influential role in the advancement of groundwater science as influenced by Dr. József Tóth who emigrated from Hungary to Canada in 1960 where—with colleagues at the Alberta Research Council—he instigated much of what resulted in modern thinking about gravity-driven groundwater flow systems. The Prairie region of Canada and the Hungarian plains have much in common hydrogeologically. The manifestations of effects of artesian driven groundwater discharge on soil salinity and vegetation are visually evident in both environments.

The authors of this book have Hungarian and Canadian associations: Dr. Almási István is principal hydrogeologist, Dome GeoConsulting Inc., Calgary, Alberta, and has Hungarian and Canadian degrees; Dr. János Szany, associate professor of hydrogeology, Department of Mineralogy and Geochemistry, University of Szeged, Szeged, Hungary, received his university education in Hungary.

John Cherry, The Groundwater Project Leader

Guelph, Ontario, Canada, August 2024

Preface

Over thirty percent of the global reserve of freshwater is held in aquifers—underground layers of water-bearing permeable rock. The groundwater that seeps in and out of aquifers is thus an important source of the water we use in our homes, industry, and agriculture.

The Pannonian Basin in central-eastern Europe hosts one of the most complex aquifer systems in the world. Parts of these aquifers are shared among nine countries that occupy various portions of the basin. Groundwater produced from *clastic* (i.e., made up of preexisting rocks) and *karstic* (i.e., limestone with dissolution features) aquifers in the Pannonian Basin is a precious resource for drinking water, agricultural use, and geothermal energy—and used by about ten million people who inhabit this area of Europe.

In this book, we take an historic viewpoint to summarize the evolution of knowledge and understanding about how moving groundwater acts as a geologic agent—able to mobilize, transport, and deposit heat and matter in the Pannonian Basin. We also introduce the hydrogeological environment--geology, topography, and climate—that determined how these complex hydro-geothermal features were formed, maintained, and exploited over nearly two millennia. Besides the abundance of potable groundwater supplies, the Pannonian Basin is most famous for the abundance of geothermal wells and spas, and modern uses of geothermal energy.

The central part of the Pannonian Basin has two vertically stacked groundwater flow regimes: a gravity-driven upper flow regime and an overpressured deep flow regime. The latter regime was discovered through petroleum explorations carried out over the last century. To promote further understanding of this phenomenon, we also include a brief introduction to the petroleum hydrogeology of the Pannonian Basin.

Hungary occupies almost three-quarters of the surface area of the Pannonian Basin. Data from Hungary are readily accessible, thus most of the data we present originate from that source. Readers are encouraged to explore further fascinating details about this basin.

Our intent in writing this book is to provide a colorful case study by taking an interdisciplinary approach to hydrogeological investigation of sedimentary basins, including insights gleaned from geology, geophysics, geochemistry, structural geology, engineering, and infrastructure. A global overview of large aquifer systems around the world is provided by van der Gun (2022), who offers a clear perspective and context. This book is part of a series of introductions to *Important Aquifer Systems of the World* prepared by The Groundwater Project.

Acknowledgments

We are very grateful for the thorough reviews, suggestions, and contributions to this book by these individuals:

- Ágnes Tahy, Water Resources Specialist at General Directorate of Water Management, Budapest, Hungary;
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- György Tóth, ret. Hydrogeologist, Geological Institute of Hungary;
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1 The Pannonian Basin

The Pannonian Basin of central-eastern Europe is famous for its vast groundwater resources, geothermal energy, and rich biodiversity. Its semi-arid climate is characterized by large grasslands and ephemeral wetlands surrounded by karst features and mazes of caves. As an intermontane basin, it contains the Pannonian Aquifer System, one of 70 aquifer systems in the world (Figure 1). Groundwater distribution and flow in this basin—while hidden in plain sight—play a fundamental role in the development and maintenance of rich fauna and flora habitats, drinking water supply, agriculture, use of geothermal energy, and accumulations of oil and gas.

In this book, we review the key geological, hydrogeological, geothermal, and petroleum geological characteristics of the Pannonian Basin from a historic perspective. This approach allows for a more nuanced context and demonstrates the interdependence of these subdisciplines. Most of the information we present is from the central region of the Pannonian Basin in Hungary. Limited information was available to us from the adjacent countries.

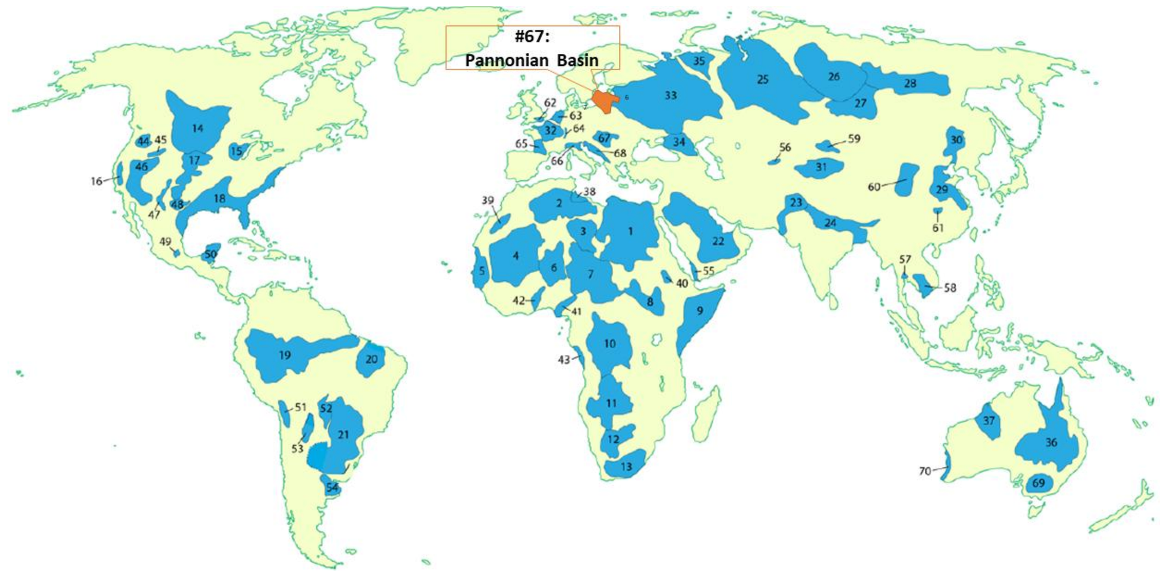


Figure 1 - The 70 large aquifer systems of the world and position of the Pannonian Basin (after van der Gun, 2022).

1.1 Overview

The Pannonian Basin in central-eastern Europe is surrounded by the Carpathian Mountains to the north and east, by the Southern Carpathians and Dinaric Mountains to the south, and the Southern and Eastern Alps to the west (Figure 2). As the Carpathian arch is the longest boundary of the basin, the Pannonian Basin is also called the Carpathian Basin in older literature.

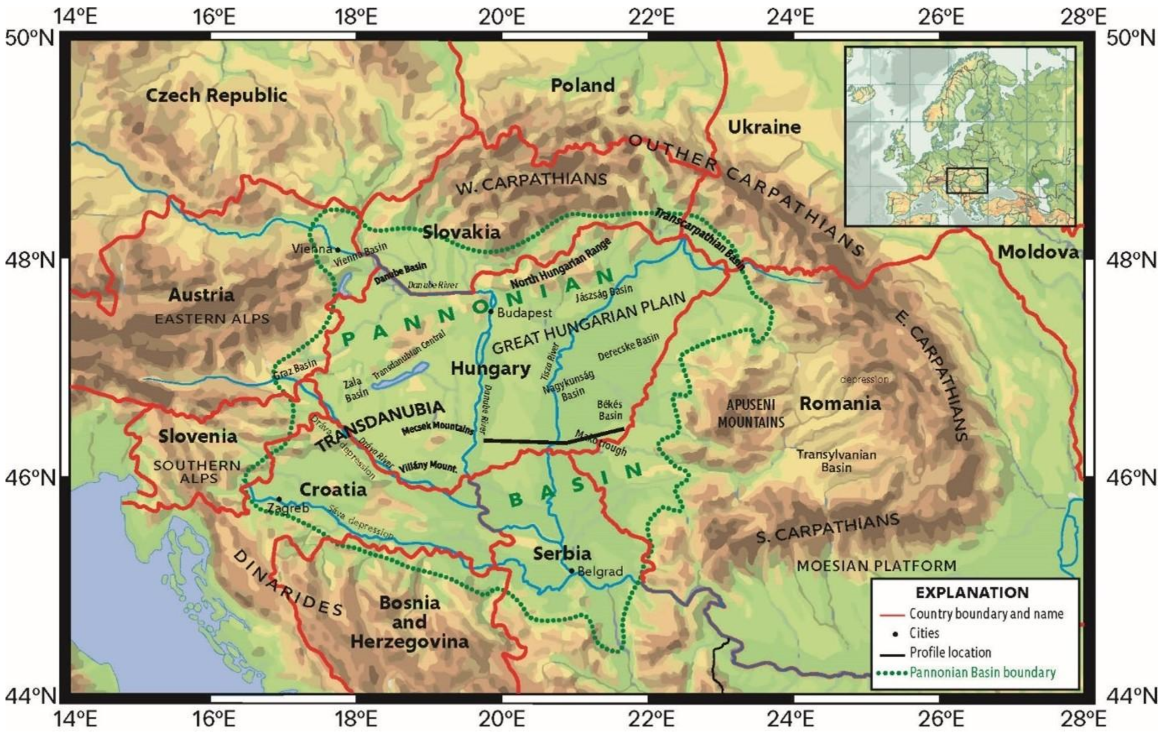


Figure 2 - Topography of the Carpathian Basin showing geographic names used in this book. Source of digital terrain model: https://geophysics.elte.hu/atlas/geodin_atlas.htm↗.

The elevations of the Alps, Carpathians, and Dinaric (also known as the Dinarides) mountain ranges exceed 2,500 m above sea level, whereas the Pannonian Basin elevation is between 78 and 200 m above sea level. The area of this intermontane sedimentary basin is approximately 230,000 km^2 and straddles nine countries. Hungary occupies the central and largest part of the basin. Smaller parts of the basin are in Slovakia to the north; Ukraine to the northeast; Romania to the east; Serbia, Croatia, and Bosnia and Herzegovina to the south; and Slovenia and Austria to the west.

Within the Pannonian Basin lie several smaller mountains and hills (e.g., Transdanubian Central Range, North-Central Range, Apuseni Mountains), which subdivide this area into physiographic sub-basins. Therefore, the Pannonian Basin is best understood as a *basin system* where these physiographic sub-basins are referred to by their geographic names (e.g., Great Hungarian Plain, Little Hungarian Plain, Styrian Basin, Vienna Basin, Danube Basin, Transcarpathian Basin, Transylvanian Basin). Our focus in this book is on the sub-basins within the green-dashed polygon in Figure 2 and excludes the Transylvanian basin that is in central Romania.

As a central intermontane depression, the Pannonian Basin system is the main catchment area of surface runoff from the surrounding mountains. The basin is drained along the middle by the Danube, one of Europe's largest rivers. Large tributaries of the Danube within the basin system include the Sava, Dráva, and Tisza rivers, which are fed by extensive networks of smaller tributaries (with headwaters in the surrounding mountains) and sub-basins at higher elevation with outlets to major tributaries. Ultimately, the basin system drains into the Black Sea via the Danube. The largest lake in the basin is the Balaton (77 km long and up to 8 km wide).

Geologically, the Pannonian Basin system is a complex extensional basin of Neogene age (23 to 2.6 Ma ago, where Ma is an abbreviation of *mega annum* meaning one million years) overlying several Mid-Cretaceous to Paleogene age sub-basins in the Alpine-Carpathian thrust and fold belt, and comprises Mesozoic and Paleozoic rocks. These structural sub-basins are separated by uplifted basement blocks and are filled by Neogene and Quaternary sediments ranging in thickness from less than 100 m to greater than 7,000 m from the surface to the top of basement rocks.

Each physiographic sub-basin includes one or several *structural geological sub-basins*. The most interesting example is the Great Hungarian Plain, a physiographic sub-basin that—beneath the surface—includes the Jászság, Derecske, Nagykunság, and Békés basins as well as the Makó trough. Other structural sub-basins in the Pannonian Basin system coincide with physiographic sub-basins.

Owing to its physiographic setting, the Pannonian Basin system is well known as a large *artesian basin* because of the abundance of flowing artesian springs and wells, where artesian refers features that penetrate a layer of lower permeability material that holds fresh water below the surface under pressure exceeding hydrostatic conditions. This large intermontane depression is also prone to seasonal flooding from rapidly rising surface water and groundwater levels recharged from the surrounding uplands.

Inhabitants of the area have relied on groundwater for over two millennia. Modern groundwater management systems were implemented in the mid-1800s when most of the basin was part of the Austro-Hungarian Empire. The objectives of early groundwater management regulations were

- communal water supply management,
- water well permitting and licensing,
- protection of mineral and medicinal water supplies, and
- protection of public health.

Each country that shares parts of the Pannonian Basin has implemented specific groundwater management policies along the lines of these general objectives, although in more nuanced terms reflecting contemporary societal and environmental needs. Shared water resources in transboundary aquifers of the Pannonian Basin are managed under bilateral agreements between neighboring countries. Of all the countries in the basin system, Hungary relies most heavily on groundwater from the Pannonian Basin.

Margat (2008), Margat and van der Gun (2013), and van der Gun (2022) classified large basins based on the size of the area, depth, and water reserves; they identified 37 *mega aquifer systems* around the world. However, they omitted the Pannonian Basin from the list despite that, on the European continent, the Pannonian Basin is comparable to the North

Caucasus Basin (230,000 km^2 and 10,000 m deep) and Pechora Basin (350,000 km^2 and 3,000 m deep) in Russia. It is also larger than the Paris Basin (190,000 km^2 and 3,200 m deep) in France, and only dwarfed by the gigantic Russian Platform Basins (~3,100,000 km^2 and up to 20,000 m deep). Thus, the Pannonian Basin can be rightfully considered a mega aquifer system of great importance to nine countries.

2 Historic Perspective

2.1 Etymology (*Origin of Names*)

Pannonia was a province of the Roman Empire in the western part of modern Hungary and adjacent areas. According to Roman customs, sparsely inhabited geographic areas were named after their characteristic landscape features. As the landscape of the lowlands in this province was dominated by wetlands, marshes, swamps, lakes, and rivers—conditions that prevailed until the mid-1800s—the Romans named this province *Pannonia* in Latin, which is derived from the early Indo-European word or pronoun *pen* describing moist, wet, mud, swamp, and water. In a similar fashion, Transylvania was named *the region across the forests* (trans = across + sylvan = forest + ia = country/land in Latin).

The presence of groundwater is often indicated by geographical names as, for example, when a spring or well is mentioned in the name of a settlement, often to advertise an abundant source of groundwater and/or potable water. We can also deduce the presence of thermal water from settlement names as *Hévíz*, which specifically means thermal and medicinal water. In the Carpathian Basin, we often come across Tapolca, Toplica, Toplice, and similar names rooted in Slavic language terms for warm water. Hydrogeologists also look for geographical names that refer to salt water, as these almost certainly indicate groundwater outflows. We find several similar occurrences in the foothills and basin areas, such as the name of a *soda lake*: *Szappanos-szék* (soapy-salty) that refers to the salinity and alkalinity of the water.

2.2 Early Observations

Large portions of the Great Hungarian Plain were uninhabitable wetlands until the middle of the 1800s, as shown in Figure 3, when surface water regulations were introduced and most of these wetlands were drained and converted to fertile agricultural lands of a prairie- or steppe-like landscape (called *puszta* in Hungarian). Starting in 1846, approximately 40,000 km^2 of flood prone area was drained, the length of the Tisza River was reduced from 1,419 km to 962 km, 196 km of new river bed was excavated, and 589 km of backwater was created. The post-drainage hydrography of the Pannonian Basin is shown in Figure 4.

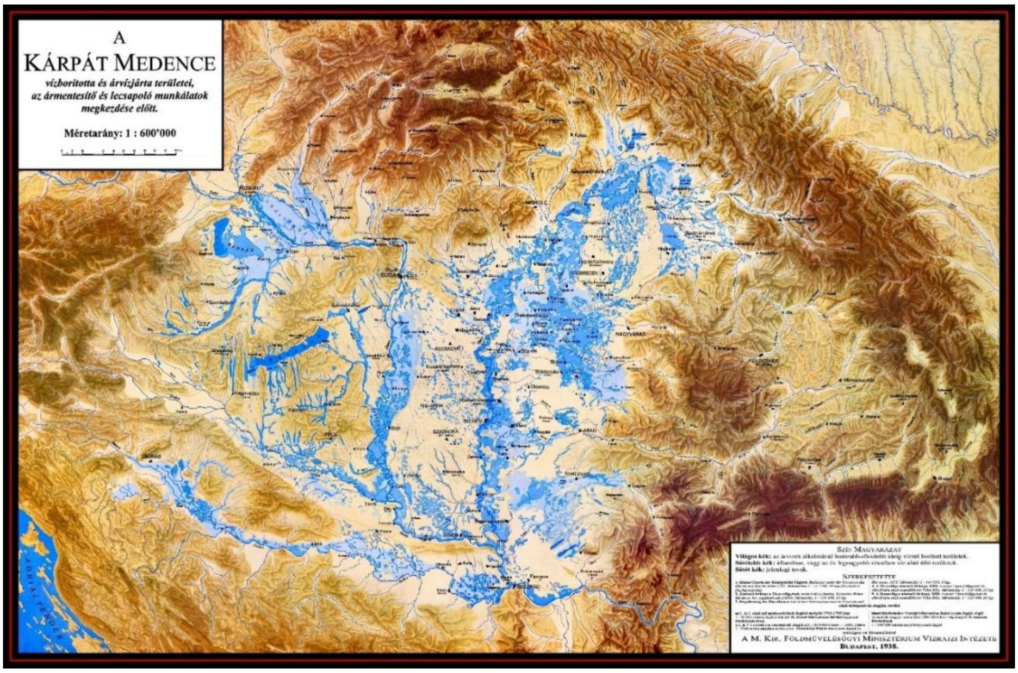


Figure 3 - Hydrography of the Pannonian Basin before river and lake regulations were enacted in the nineteenth century (The Hydrographic Institute of the Royal Hungarian Ministry of Agriculture, 1938; https://map.mbfsz.gov.hu/terkepekamultbol/Mo_arviz_1938/↗).

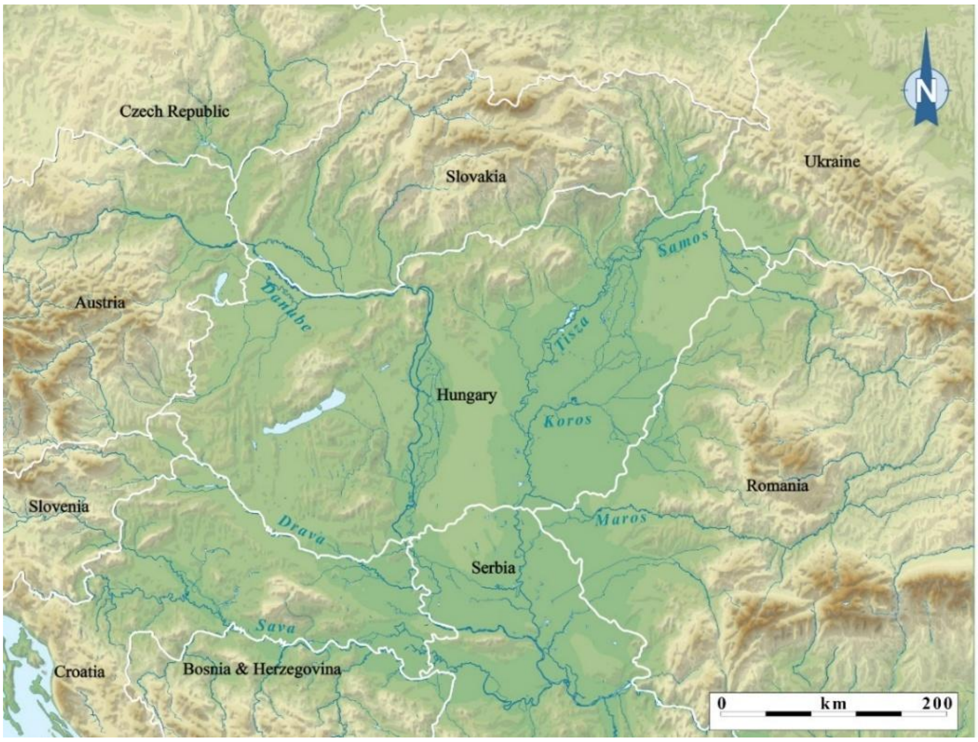


Figure 4 - Hydrography of the Pannonian Basin after river and lake regulations were implemented. Annotated source map from https://commons.wikimedia.org/wiki/File:Pannonian_Basin_geographic_map_blank.svg↗.

With limited access to surface water, the growing rural and urban population relied primarily on groundwater from dug wells. Owing to the shallow water table in the sandy areas of the plains region, draw or sweep pole became a common and convenient means for water withdrawal (Figure 5a). Such wells are still in use today on small farms and in some villages (Figure 5c and d).

Flowing artesian conditions were recognized by the mid-1800s, and large yield wells were commissioned for the water supplies of cities. Such wells were not only practical sources of water but also urban ornaments such as one found in Szentes, Hungary (Figure 5b). This well was drilled between 1885 and 1886 to 312 m below surface, which was considered an impressive engineering feat for its time.

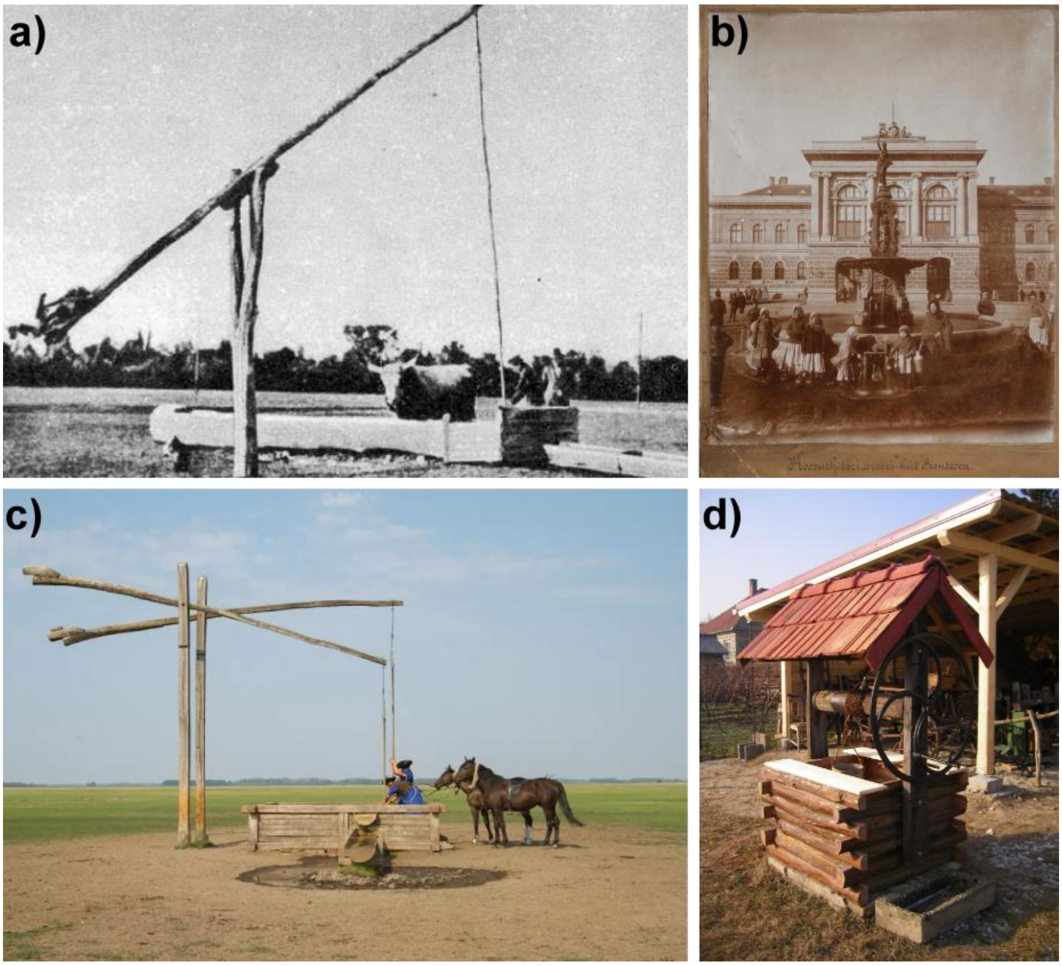


Figure 5 - a) Draw (or sweep pole) well, late 1800s. b) Artesian well drilled in 1886 to a depth of 312 m in Szentes, Hungary. c) Modern day sweep pole well. d) Cable-wheel well (Bulgarian type). Photo credits:

a) https://www.arcanum.com/hu/online-kiadvanyok/Lexikonok-magyar-neprajzi-lexikon-71DCC/g-72839/gemeskut-72880/↗

b) https://hu.wikipedia.org/wiki/F%C3%A1jl:Kossuth-t%C3%A9ri_%C3%A1rt%C3%A9zi_k%C3%BAt_Szentesen_%281886-1934%29.jpg↗

c) https://blog.szallas.hu/lora-fel-avagy-irany-hortobagy/↗

d) https://commons.wikimedia.org/wiki/File:Dunamocs094.JPG ; Szeder László, CC BY-SA 4.0 <https://creativecommons.org/licenses/by-sa/4.0>, via Wikimedia Commons↗

By 1900, thousands of artesian wells were drilled across the plains, producing lukewarm to warm water with reduced mineralization in seemingly endless quantities. Unbridled use of groundwater from artesian wells, combined with a suddenly increasing population density and rudimentary sewer systems, led to water management and public health problems. Thus, groundwater management regulations were introduced in 1885 by the Royal Hungarian Geological Institute for communal water supply management, water well permitting and licensing, and protection of mineral and medicinal water supplies. The Geological Institute followed this in 1892 by forming a hydrological department for the management of artesian wells. After the breakup of the Austro-Hungarian Empire in 1919, the newly-independent countries that shared the aquifers of the Pannonian Basin set up national water management agencies and institutes.

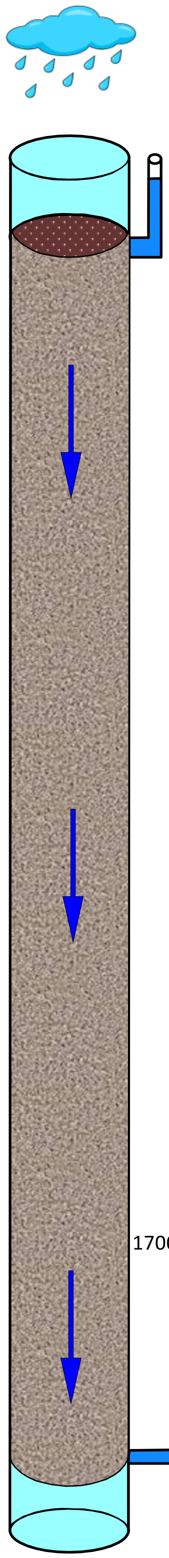
The Pannonian Basin is also well known for karst springs issuing from Mesozoic limestone and dolomite in the intra-basin mountains. Several cave networks are found in the Buda Hills, Aggtelek, and Apuseni Mountains. The waters of their high-yield karst springs are used for human consumption and therapeutic spas (Figure 6). There are several dozen thermal spas across the basin (e.g., active thermal spas of Hungary are introduced at https://termalonline.hu/↗) Karst aquifers are also associated with bauxite and coal mines in the Transdanubian Central Range, Apuseni Mountains, and the Dinarides.

a) **b)**

Figure 6 - a) Karst spring in a cave (Miskolctapolca, northeastern Hungary. b) Thermal waters in a Turkish bath, Budapest, Hungary. More information on thermal spas of Budapest can be found at https://www.budapestgyogyfurdoi.hu/↗.
Photo credits:
a) https://termalonline.hu/furdok/miskolctapolca-barlangfurdo; photo courtesy Zsolt Varga↗
b) https://www.termalfurdo.hu/furdozes/rejtett-kincsek-budapesten-tudta-hogy-ezek-a-furdok-is-muemlekek-4708↗

Water wells drilled to depths of about 500 m in the Great Hungarian Plain often produced warm water with various amounts of natural gas (Rónai, 1964). Even shallow wells—less than 5 to 10 m deep—often produced some natural gas, mostly methane and carbon-dioxide. These early gas manifestations were the first signs of potential deep gas accumulations in the basin. These discoveries led to the onset of oil and gas exploration in the early 1920s by British and American companies.

The nature of geological data collected, and depth ranges explored, in the basin varied according to the interests and mandates of each company or institute. Since the mid-1800s, vast amounts of hydrogeological data have been acquired across the basin. Thus, the data available for the Pannonian Basin system make it an ideal region for investigating certain manifestations of groundwater flow as they relate to drinking water resources, agriculture, land management, wetlands, geothermal energy distribution, and hydrocarbon accumulations.



Pannonian Basin Hydrogeological Events Timeline

2012-2018	Water treatment projects.
2018	First geothermal power plant commissioned.
2017	*The Groundwater Project launched.*
1995-2001	Petroleum hydrogeology of the Great Hungarian Plain - first integrated basin scale study (Tóth & Almási).
1994	The Danube River Protection Convention was introduced.
1990	Hungary's groundwater production peaked at 40% higher than current levels.
1965-1970	Discovery of greatly overpressured reservoirs.
1965	First significant oil and gas accumulation of real commercial value.
1940	Hungary had 24,000 artesian wells.
1936	The first international balneological congress was organized in Budapest.
1925	Petroleum exploration led to the discovery of medicinal thermal water in Hajdúszoboszló.
1920	Establishment of national water management entities in many Pannonian Basin countries.
1907	Discovery and use of petroleum.
1900	Hungary had 2,400 artesian wells.
1885	Initial groundwater regulations and governance, focusing on springs and medicinal waters.
1879	Initial deep well drilling.
1860-1930	Majority of the famous medicinal thermal water resources were established.
1868 - 1878	Europe's second-deepest geothermal well was drilled for the Széchenyi Spa in Pest, to a depth of 970 m and produced water temperature of 74 ºC.
1865	First drilled thermal water well 38 m deep, yielding 249 m^3/day of 62.5 ºC water).
mid-1800's	Initiation of irrigation using wells.
1860?	Initial episodes of locating wells along rivers.
1834 - 1945	River regulations introduced to control floods, enhance navigability of major rivers, increase the area of arable land. Wetlands and lakes were drained, meandering rivers diverted into canals.
1825	First drilled flowing artesian water well, producing mineral water with NaCl, I, and CO_2.
1762	Royal order for the "inventory, mapping, and quality analysis of all mineral water in the Carpathian Basin".
1735	The world's first Mining and Metallurgical Academy (Bergschule) was established teaching "mine drainage" as one of its core subjects.
	Historical Geography documented medicinal waters and dug wells.
1700's or earlier	Discovery and use of mineral and thermal waters.
1696	First dug well in the Buda Castle.
1663	First recorded analysis of mineral water at Besztercebánya (Banská Bystrica).
1650-1654	First written record of dug wells by János C. Amos.
1500s	Nine Turkish baths were built in Buda (five still exist today, and four are actively used).
1178	Knights of Malta built a bath on the site of Császár Bath at the Buda Springs (Budapest).
~479	Byzantine historian Priscus Rhetor described the stone baths of Attila the Hun.
200	First documented use of geothermal spring waters for heating and bathing by Roman legionaries.

Table 1 - Timeline of hydrogeologic events in the Pannonian Basin.

3 Formation of the Pannonian Basin

The Pannonian Basin evolved during the Neogene as an integral part of the Alpine, Carpathian, and Dinaric orogenic (i.e., mountain building) system. The Neogene sedimentary basin is superimposed on a thrust and fold belt dating from a mid-Cretaceous period that consists of Mesozoic and Paleozoic rocks genetically related to the surrounding mountains (Royden and Horváth, 1988; Sztanó and Tari, 1993; Horváth et al., 2006; Haas et al., 2013).

Due to the uplift of the Dinaric and Southern Alps, the Intra-Carpathian region was temporarily isolated from the Mediterranean at the end of the Oligocene (~26 Ma ago). Later—during the Miocene—the basins and inland seas of the Intra-Carpathian region were repeatedly isolated from the Mediterranean. This isolated area is called *Central Parathetys* and comprises the present territories of the Pannonian and Transylvanian Basins (e.g., Kovac et al., 2017).

During the Miocene, while the Alps, Carpathians, and Dinarides were uplifting under compression, the Pannonian Basin was subsiding under extension and rifting. Because of intense erosion of the mountains, over 7,000 m of thick (mainly clastic) sediments were deposited in the basin. These sediments comprise most aquifers and hydrocarbon reservoirs of interest in the basin.

Subsidence by rifting commenced by the end of the early Miocene (19 to 17.5 Ma ago) and ended approximately 14 Ma ago in the middle Miocene. Rifting caused thinning of the lithosphere followed by upwelling of the semi-molten asthenosphere; the average thickness of the lithosphere and crust of the Pannonian Basin is only ~60 km and ~25 km, respectively. The thin lithosphere under the basin is associated with an anomalously high heat flow (i.e., a heat flow that deviates from normal heat flow of 50 to 80 mW/m^2, being on the order of 80 to 120 mW/m^2.

The style and degree of extensional deformation of the crust vary throughout the Pannonian Basin. Several structural sub-basins were formed, separated by basement highs, and displaying a *Basin and Range-like* topography. Some sub-basins developed as rift basins, bounded by normal faults; other sub-basins developed as pull-apart basins. Once rifting ceased, subsidence continued because of thermal cooling that occurred during the late Miocene and early Pliocene. From the late Pliocene to the present day, the stress regime in the region has been predominantly compressional (Figure 7 and Figure 8).

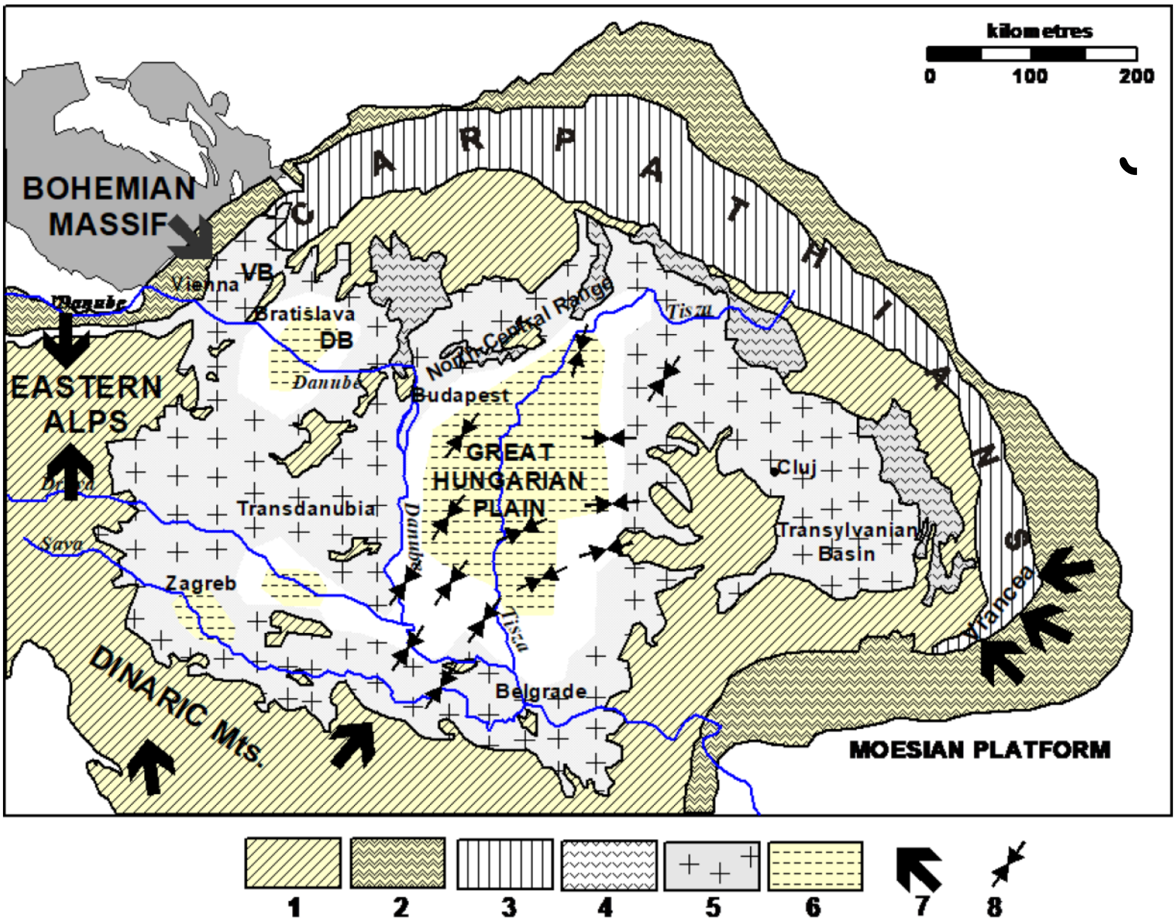


Figure 7 - Recent configuration of the Pannonian Basin and the associated Alpine Mountain belt. The pattern of the Quaternary vertical movements is also shown. (modified after Horváth, 1995; directions of block motion and compressive stress are taken from Bada et al., 1998). The Moesian platform acts as a rigid buttress, while the Western and Northeastern Carpathians are 'free.'

Symbols:

1 = inner Alpine, Carpathian, and Dinaric Mountains;
2 = Alpine and Carpathian molasse foredeep;
3 = Alpine and Carpathian flysch belt;
4 = Neogene calc-alkaline volcanic rocks;
5 = area of Quaternary uplift;
6 = area of Quaternary subsidence;
7 = directions of present-day tectonic push;
8 = present-day direction of maximum horizontal compressive stress

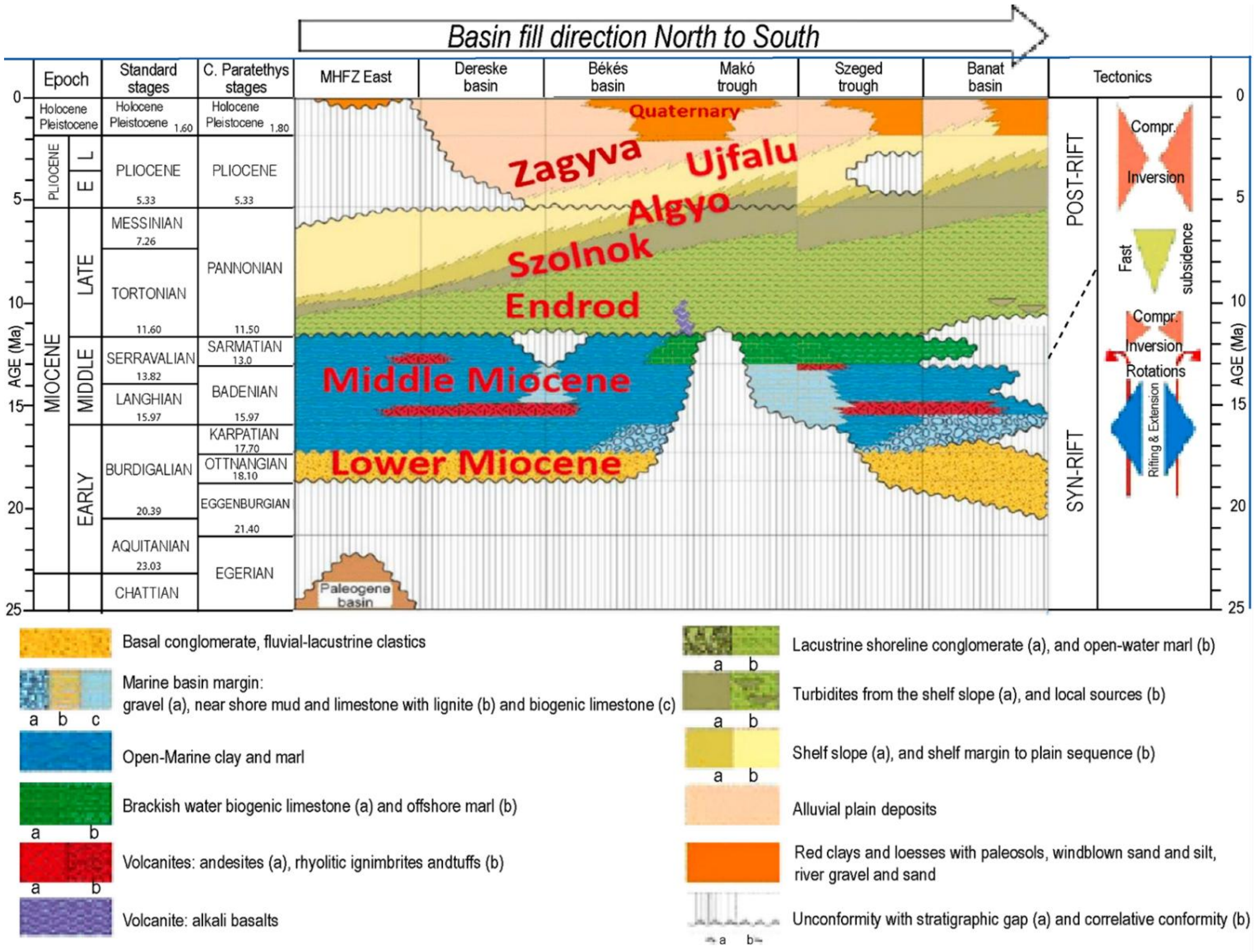


Figure 8 - Stratigraphic chart and tectonic evolution of the Pannonian Basin in the Neogene to Recent (modified after Horváth et al., 2015, and Bogicevic et al., 2020).

By the end of the Pliocene (~2.4 Ma ago), the basin was uplifted; fluvial and deltaic sedimentation began. The Danube River deposited its load in the deepest part of the sub-basins, which resulted in 600 to 650 m thick fluvial sediments. During the Pleistocene, local-scale tectonic events coincided with higher-frequency climatic changes leading to cyclical fluvial sedimentation and a gradual shift of depositional centers. Humid, warm, or mild periods of heavy precipitation were characterized by coarse sediment deposition and cold periods by fine-grained sediment deposition. The present relief was formed at the end of the Pleistocene by uplift of the area between the Danube and the Tisza Rivers (Figure 7) (Varsányi et al., 2011).

4 Hydrogeology

Groundwater distribution and movement as well as natural phenomena linked to groundwater flow are determined by the regional and local hydrogeological environment, i.e., by climate, topography, and geology. The complex interactions and effects of these determining factors are described in the following sections.

4.1 Climate

The climate of the Pannonian Basin is continental-temperate with mild winters (low of -10 °C) and relatively hot summers (highs near 40 °C). In most parts of the basin, mean air temperature ranges from 3 to 5 °C in winter and 17 to 18 °C in summer, with the mean annual air temperature lying between 9.3 and 10.8 °C. In mountainous regions surrounding the basin, the climate is temperate, but the winters are much colder (-20 to -30 °C); summers are cooler and annual precipitation is higher than in the low-lying areas. The hottest part of the Pannonian Basin is in the Belgrade region of Serbia, where the mean annual air temperature is 12.8 °C and the average annual precipitation is close to 700 mm/yr.

The average annual precipitation ranges from 490 to 627 mm/yr (~ 80 percent is rain); however, the actual evapotranspiration ranges from 513 to 622 mm/yr, while the potential evapotranspiration ranges from 750 to 900 mm/yr.

4.2 Topography

The topography of the plains within the Pannonian Basin is characteristically flat (Figure 9), with a regional relief of about 0.1 to 3 m/km and a mean elevation of ~110 masl (meters above sea level). Approximately 68 percent of the area of the Pannonian Basin is lowland with elevations below 200 masl. Hilly areas of 200 to 400 masl elevation cover approximately 30 percent of the basin (Figure 10); mountains with elevations above 400 masl occupy about two percent of the area (Figure 11). The Little Hungarian Plain in the west, the Danube (*Duna* in Hungarian) River Valley from Budapest to Baja, the Vojvodina plain in Serbia, and the area east from the Tisza are the main lowlands, with elevations of 78 to 110 masl. These lowlands also include the intra-mountain basins mentioned earlier (Figure 2).

Figure 9 - Puszta: plains/steppe in the Pannonian Basin (http://kurultaj.hu/2013/08/ii-osok-napja-hazirend/puszta/↗).

Figure 10 - Low elevation hills (200–400 masl) in northern Hungary (photo by György Pósfai).

Figure 11 - High Tatra Mountains (Carpathians) with elevations above 400 masl bordering the Pannonian Basin. https://commons.wikimedia.org/wiki/File:High_tatras_slovakia.jpg↗.

The Duna-Tisza Interfluve area is an elongated saddle-shaped topographic high with elevations of 110 to 170 masl that starts from the Vojvodina plain in Serbia and continues northward in the Gödöllő Hills (z_0≈220 masl, where z_0 is ground elevation), then farther toward the north-east in the foothills of the North-Central Range (z_0≈250 masl). In the Nyírség region (northeastern part of Hungary), elevations do not exceed 160 masl. In the elevated hilly areas, such as the Transdanubian Central Range (z_0≈160 to 710 masl) and the hills west of the Danube (z_0≈160 to 400 masl). The local relief in the hilly areas ranges from 10 m/km to 100 m/km.

4.3 Soils

The generalized soil types of the Hungarian part of the basin are shown in Figure 12. The richest agricultural soils (such as chernozem) are typically associated with floodplains of rivers and wetlands. The best agricultural soils are found in the previously flooded low-lying areas of the basin shown in Figure 2. Elevated and forested areas are commonly covered by acidic and *solonchack*—characterized by high levels of soluble salts—type soils of lesser agricultural value that are well drained.

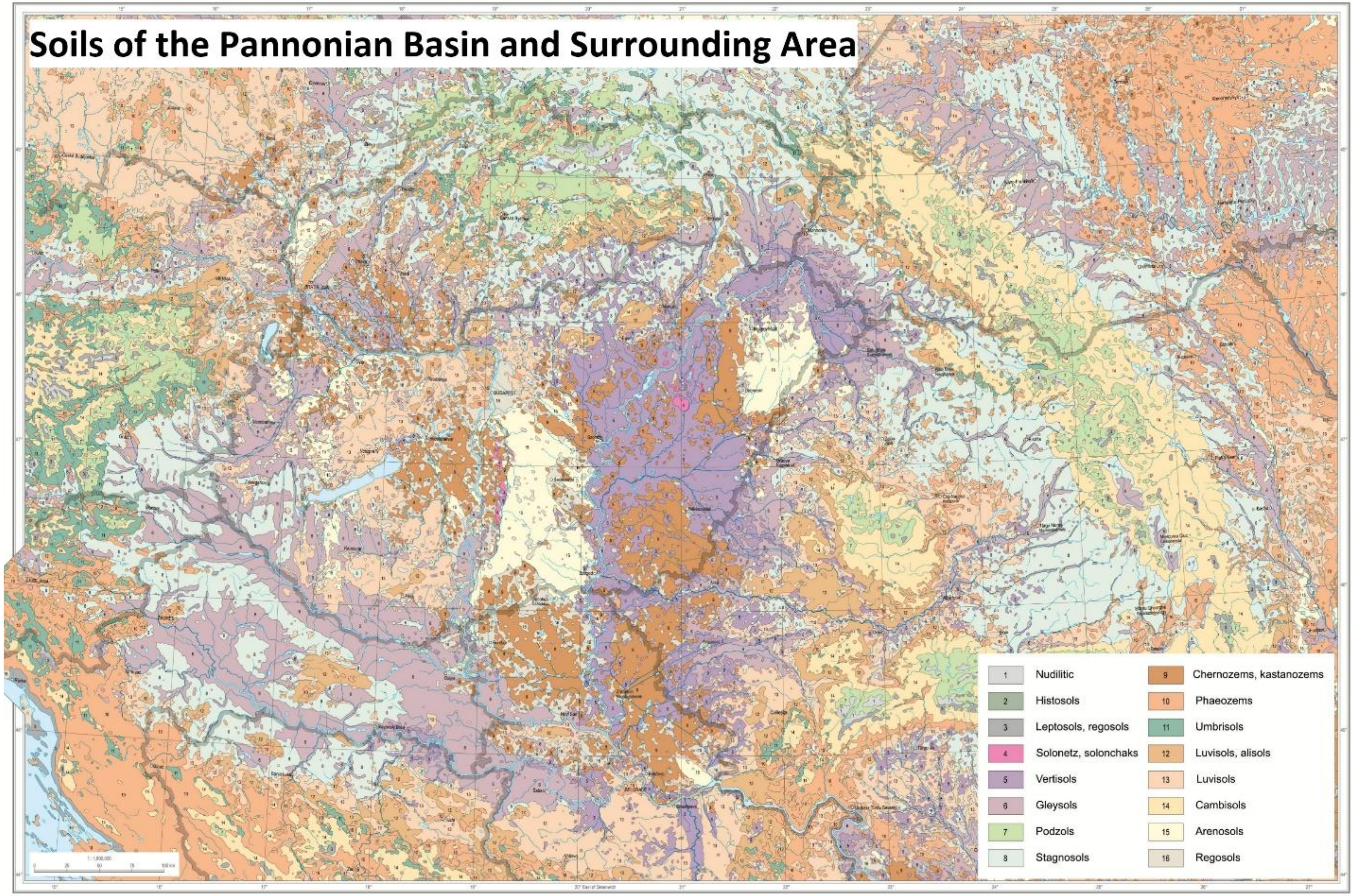


Figure 12 - Soil types within and around the Pannonian basin (modified after Kocsis, 2018). Soil types are described on the next page.

Map #	Type	Description
1	Nudilitic	eroded surfaces
2	Histosols	consists mainly of organic materials (peat)
3	Leptosols, regosols	thin with coarse fragments, very shallow, formed on hard rock
4	Solonetz, solonchak	clay rich soils, with high sodium concentrations
5	Vertisols	high content of shrinking-swelling clays, alternating wet and dry conditions
6	Gleysols	saturated with groundwater, common in wetlands
7	Podzols	subsoil accumulation of organic matter
8	Stagnosols	mottled soils in stagnant water
9	Chernozems, kastanozems	black soil, with high humus, phosphorous, and ammonia content, very fertile, excellent for agriculture
10	Phaeozems	humus rich soils, leached chernozem
11	Umbrisols	dark topsoil, mountainous areas
12	Luvisols, alisols	highly acidic soils
13	Luvisols	clay rich brown soils
14	Cambisols	early soil formation, good agricultural land
15	Arenosols	unconsolidated sand, shifting sand dunes
16	Regosols	very weakly developed soil, found in arid and semi-arid areas

4.4 Geology

The Pannonian Basin contains clastic sedimentary rocks reaching a thickness of up to 7 km deposited during the Neogene and Quaternary—i.e., during the past 17 Ma—on top of a heavily deformed Pre-Neogene basement. The Pre-Neogene basement rocks consist of indurated rocks (i.e., hardened by cementation and compaction) of various origins, mainly crystalline and carbonate rocks.

Clastic sediments originating in the elevated Carpathians were deposited in a lacustrine environment. The basin was filled by two delta systems prograding from the Carpathian arc toward the center; one delta system moved in from the northwest and another from the northeast. The northwestern delta system became dominant after about 6 Ma. Smaller delta systems may have developed from other directions. From time to time, as sediment continued to accumulate in the Pannonian Basin, the level of the lakes fluctuated. Additionally, the earth's crust lowered to different levels in different parts of the basin and the sources of sediment flowing into the basin moved/changed location along the same plane.

The Neogene-Quaternary sedimentary sequence consists of seven depositional units (Figure 13). From bottom to top, these deposits are a basal unit, a deep basin unit, a prodelta turbidite unit, a delta slope unit, a delta front-delta plain unit, an alluvial plain unit, and a terrestrial unit. These deposits are of the delta facies type, which is a cone-shaped depositional system that forms where a river flows into an ocean or lake (Magyar et al., 1999; Pigott and Radivojevic, 2010). The formation names in Figure 8 serve as examples for the terminology used in the Great Hungarian Plain (also Figure 13). Other sub-basins and countries may use different names for the same or analogous facies, however, and the formation names undergo periodic reviews and updates. Thanks to transboundary aquifer management cooperation with neighboring countries, the Hungarian terminology has been gradually adopted across the Pannonian Basin for consistency in mapping the extent of these formations.

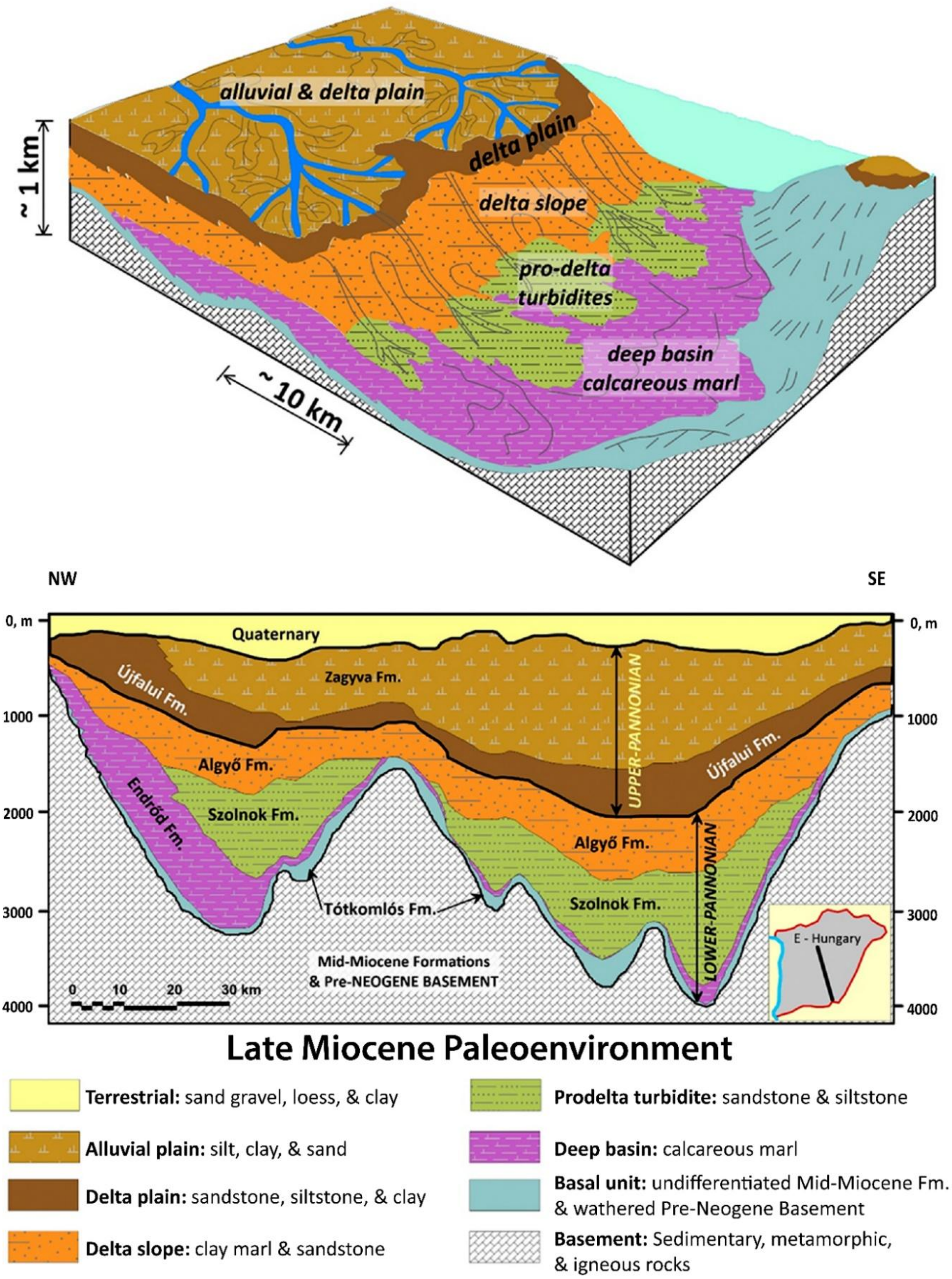


Figure 13 - Geological block diagram (above) and cross-section (below) of the Great Hungarian Plain sediments and stratigraphy in the late Miocene (based on Juhász, 1991; Tóth and Almási, 2001). The location of this cross section is indicated in the map inset.

4.5 Hydrostratigraphy

Three regional aquifers and two regional aquitards were identified in the Pannonian Basin, apart from carbonate aquifers. These regional hydrostratigraphic units (Table 2) may not apply to local scale (1–100 km^2) investigations; they should be modified or refined according to the scale of future studies, as necessary.

Table 2 - The five regional hydrostratigraphic units of the Pannonian Basin and their bulk hydraulic conductivity, K.

Regional hydrostratigraphic units	Bulk hydraulic conductivity
The Nagyalföld Aquifer	sandy units $K \approx 10^{-5} – 10^{-3}$ m/s; clayey units $K \approx 10^{-9} – 10^{-6}$ m/s (delta and alluvial plain sediments with terrestrial sediments and Upper Pannonian and Quaternary deposits)
Algyő Aquitard (leaky) (delta slope sediments)	$K \approx 10^{-8}$ m/s
Szolnok Aquifer (prodelta turbidite sediments)	$K \approx 10^{-7} – 10^{-5}$ m/s
Endrőd Aquitard (deep basin sediments)	$K \approx 10^{-10} – 10^{-8}$ m/s
Pre-Pannonian Aquifer (basal sediments)	$K \approx 10^{-6} – 10^{-5}$ m/s

An impermeable basal boundary is assumed to exist at a certain depth within the Pre-Neogene basement. The five regional hydrostratigraphic units listed in Table 2 were defined in the Hungarian part of the Pannonian Basin (Figure 14) and are listed from shallow to deep. Formation names vary by country outside Hungary, but the depositional environments are largely the same and used as sedimentological reference (i.e., in the study of sediment grains). Both the regional aquifers and aquitards consist of an irregularly alternating sequence of smaller) *lenticular* aquifers and aquitards (i.e., having a lens-shaped cross-section). Local hydraulic conductivity values depend on lithology (i.e., general physical characteristics) and size of rock; thus, these local values can differ by several orders of magnitude from the bulk average values shown in Table 2. The Nagyalföld Aquifer is a complex regionally unconfined aquifer that encompasses Quaternary and Upper Pannonian deposits. The Algyő Aquitard is a regional confining unit. thus, all aquifers beneath the Algyő Aquitard are regionally confined. Vertical hydraulic communication between the regional aquifers is tectonically enhanced across the regional aquitards which are considered *leaky*, that is, aquitards that transmit water at a slow rate between adjacent aquifers.

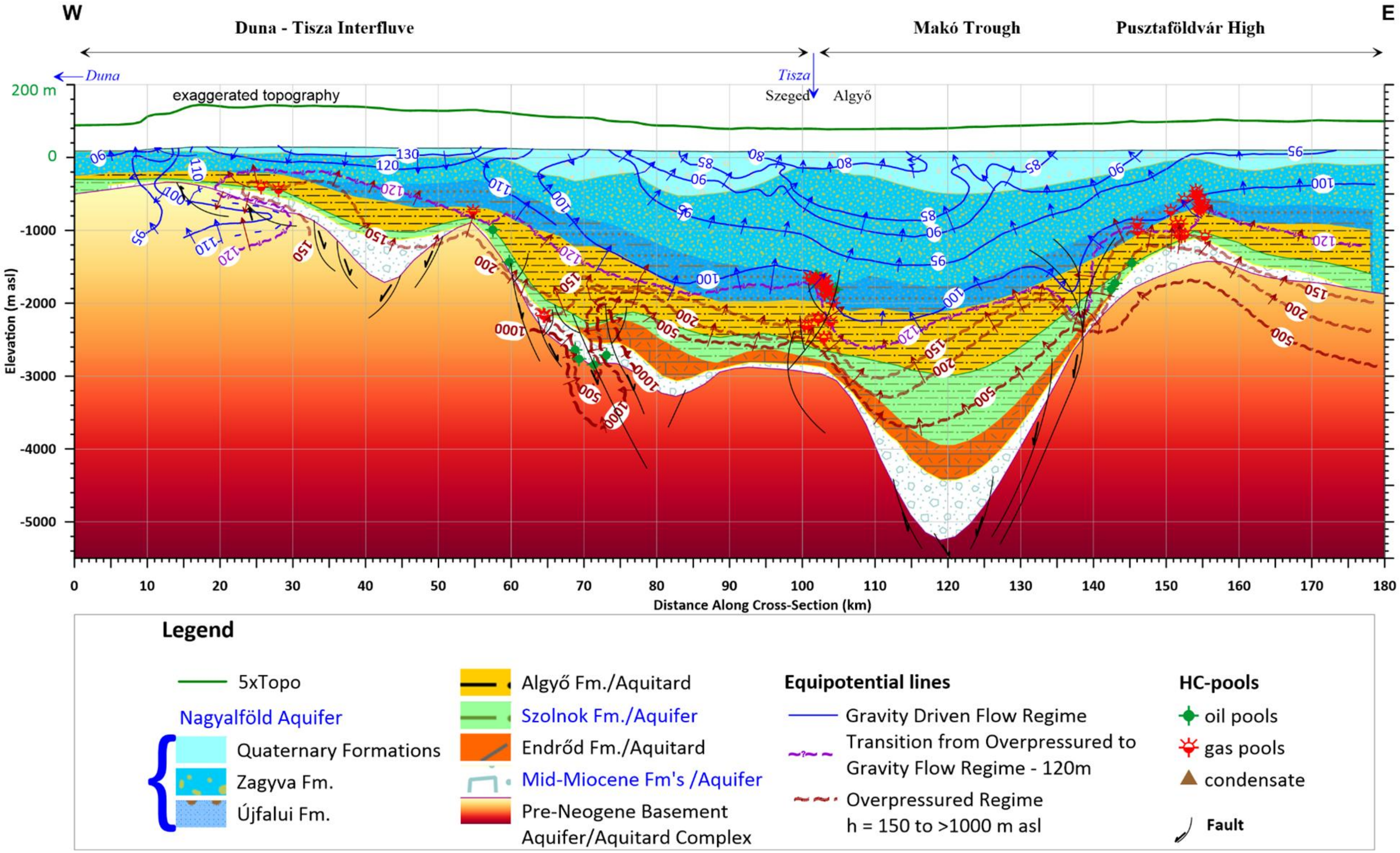


Figure 14 - Schematic hydrostratigraphic profile across the Great Hungarian Plain (modified after Almási, 2001). The color scheme represents the geothermal conditions in the basin. The location of the section is shown in Figure 2, where it is labeled 'profile location'.

4.6 Groundwater Flow Systems

The theory of regional groundwater flow was developed by József Tóth—now professor emeritus of the University of Alberta—in 1962 and 1963. He was born and raised in the town of Békés in the east-central part of the Great Hungarian Plain and emigrated to Canada in 1960. Professor Tóth developed and field tested his theory while employed by the Alberta Research Council as a hydrogeologist from 1960 to 1980, where he was Head of the Groundwater Department between 1968 and 1980.

Tóth's theory was based on the analytical solution of the Laplace equation in two dimensions applied to a cross-section. He assumed basal and lateral *no flow boundaries* and a linearly-sloping water table that mimics the topography of the area, within a hydraulically isotropic and homogeneous rock framework (i.e., the permeability or hydraulic conductivity is the same in every point of the flow domain).

The sloping water table means a potential energy difference exists between the *high ground* and the valley; gravity drives fluid flow. In such a simple *unit basin*, groundwater flow is directed downward under the elevated *recharge area,* laterally through the mid-section (*midline*), and upward beneath the low-lying area called *discharge area* (Figure 15). The depth of the basal no-flow boundary is arbitrary in a mathematical sense; however, in natural geological conditions, it can be conceived of as the interface of strata having a permeability contrast of at least two orders of magnitude. The lateral no flow boundaries are created by the symmetry underneath a watershed divide in the recharge area and a surface water thalweg in the discharge area.

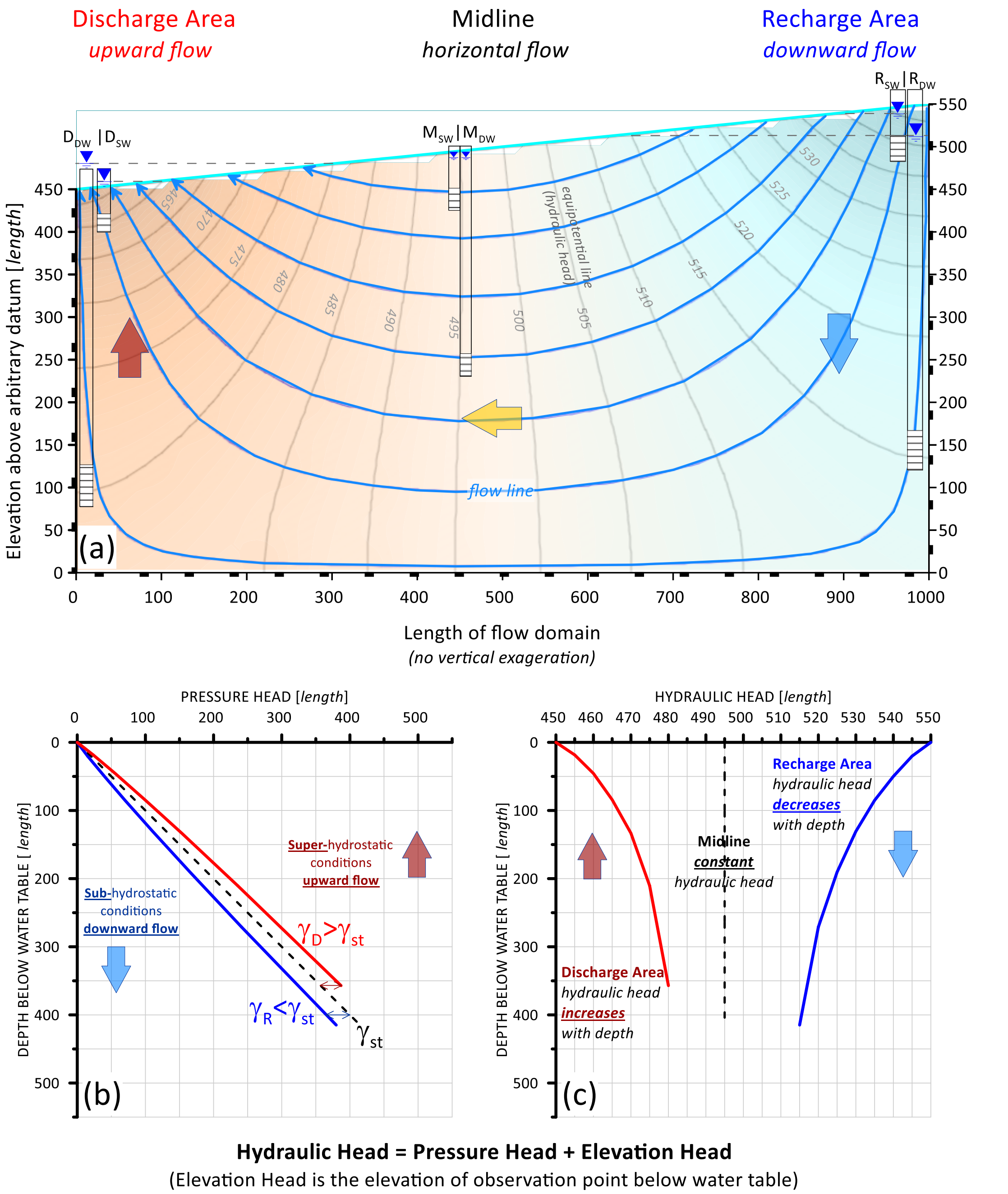


Figure 15 - Conceptual diagram of groundwater flow in a unit basin (modified after Tóth, 1962 using TopoDrive software; which is discussed by Poeter and Hsieh, 2020, gw-project.org). a) Profile of the unit basin with solid blue lines with arrows illustrating groundwater flow paths, and grey lines representing equal hydraulic head (i.e., the level that water will rise to in a pipe open to a discrete point in a flow system). Hydraulic head is higher in the recharge area and lower in the discharge area. Hydrostatic conditions occur at the midline of the basin where head is constant with depth and flow is horizontal, so the water level is the same in the shallow monitoring well (M_{SW}) and the deep monitoring well (M_{DW}). In recharge areas, water level in the shallow well (R_{SW}) is higher than in the deep well (R_{DW}) as the hydraulic head decreases with the increase of well depth due to downward flow. In discharge areas the hydraulic head increases with depth, so the water level in the deep (D_{DW}) is higher than in the shallow well (D_{SW}), as flow is upward. b) Pore pressure can be expressed as the height of a column of water above a point of observation (e.g., bottom of a well), and equals the difference between hydraulic head and elevation at that point location. Pressure always increases with depth, and the rate of increase of pressure with depth is called the pressure gradient (γ). Under horizontal flow conditions the pressure gradient is hydrostatic (γ_{ST}), that is, the pressure increases at the same rate as the elevation decreases. Under vertical flow conditions, the dynamic pressure gradient in a recharge area (γ_R) is smaller than the hydrostatic gradient (γ_{ST}), and in a discharge area (γ_D) is larger than the hydrostatic gradient (γ_{ST}). c) Hydraulic head is the sum of the pressure head and the elevation head, leading to the increasing head with depth in the discharge area and decreasing head with depth in the rechange area.

A particular solution to Tóth's equation was calculated for a regionally sloping and undulating (sinusoidal) water table boundary condition. It is assumed that the water table mimics the topography, albeit deeper beneath mounds and shallower—if not above—local depressions. Thus, the geometry of the flow paths is determined by the surface relief and permeability of rocks (Figure 16). The regional slope and local relief induces a set of hierarchically-nested flow systems: Local, Intermediate, and Regional.

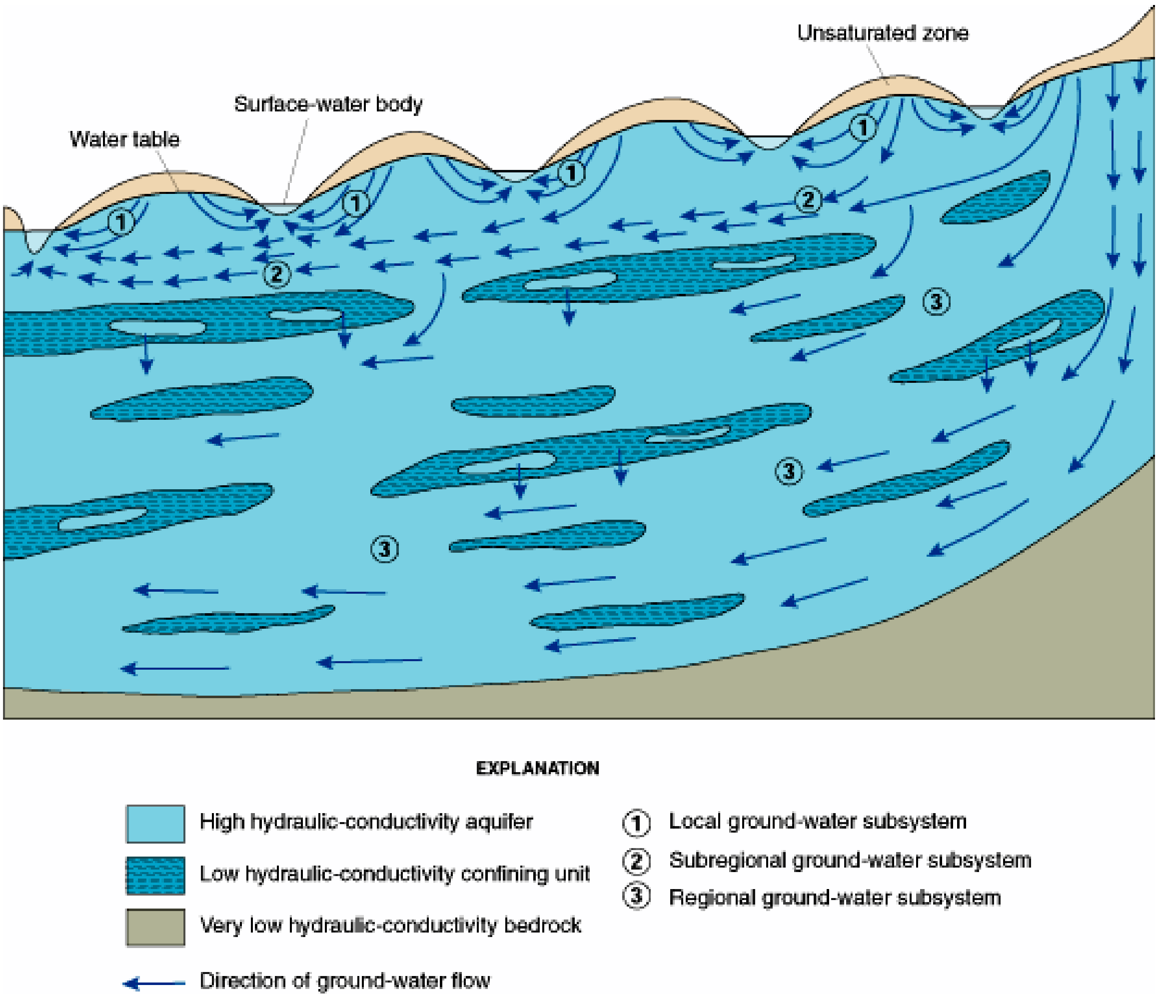


Figure 16 - A gravity-driven regional groundwater-flow system that comprises subsystems at different scales and a complex hydrogeologic framework (modified from Sun, 1986). Arrows indicate general flow direction (illustration from https://pubs.usgs.gov/circ/circ1186/html/gen_facts.html↗).

Groundwater flow paths vary greatly in length, depth, and travel time from points of recharge to points of discharge in a groundwater system. In Figure 16, geological and hydrostratigraphic variations within a flow domain are illustrated as lenticular bodies of higher and lower permeability within the matrix of the general flow domain. Flow lines of every hierarchical system tend to follow the paths of least resistance. Readers are encouraged to explore the influence of the shape of the water table as well as the geometry and hydraulic conductivity of hydrostratigraphic variations using the interactive exploration tool called TopoDrive↗ that is provided through The Groundwater Project. The Groundwater Project also provides a 15-minute video describing the use of TopoDrive↗.

The chemistry and temperature of moving groundwater changes along the flow paths. Figure 17 illustrates the common and typical changes expected in the subsurface, where the moving groundwater can dissolve, mobilize, transport, and accumulate matter and heat; some of the near-surface features caused by discharging groundwater are also shown.

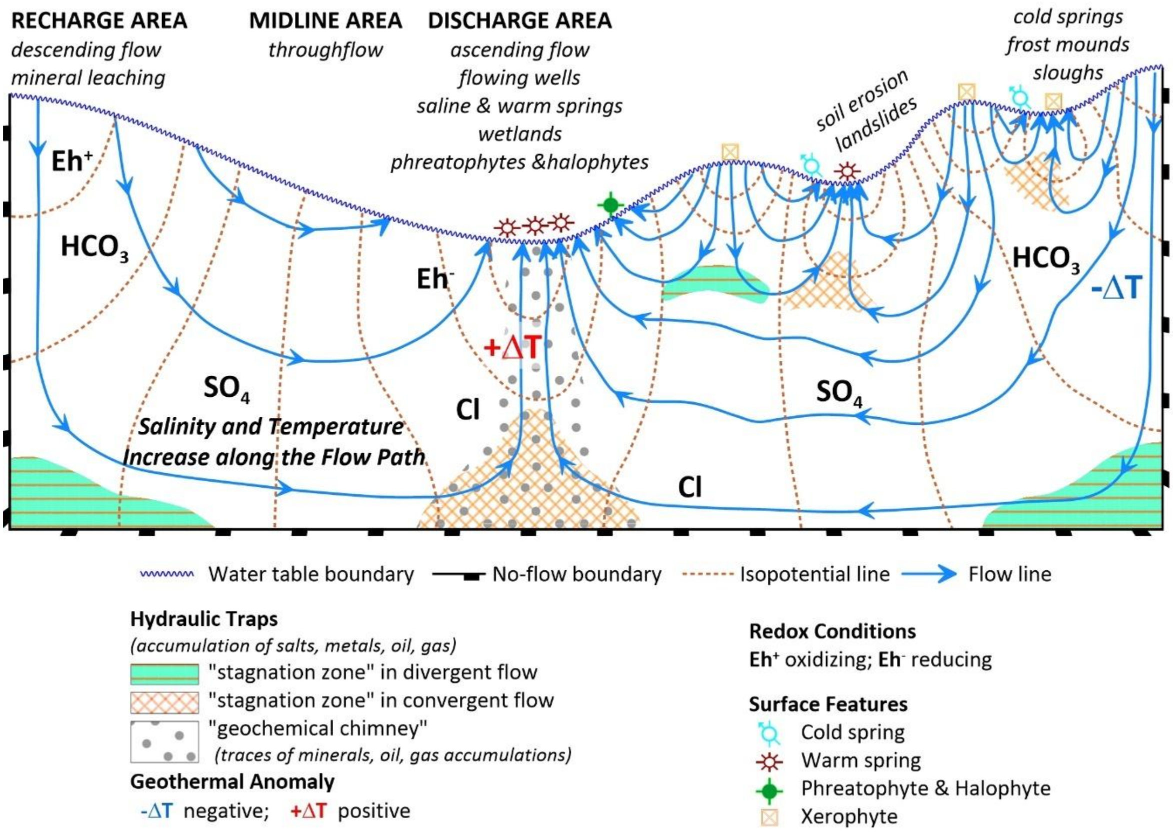


Figure 17 - Manifestations and effects of gravity-driven groundwater flow in an unconfined sedimentary basin. The east side illustrates the influence of local topographical variations. (modified from Tóth, 1999).

These near-surface features are the result of several different factors. For example, the salinity of groundwater is influenced by the velocity of groundwater flow and the soluble minerals encountered along the flow paths. Slow moving water has a longer *residence time* during which to dissolve large quantities of available soluble salts when compared to more vigorous flow systems that have shorter residence times and interactions with the rock framework. Thus, the Total Dissolved Solids (TDS) concentration of groundwater beneath recharge areas is characteristically lower than the TDS observed in discharge areas. In other words, as slow-moving groundwater has more time to pick up salts, the concentration of salts is higher down gradient. For a thorough discussion on the chemical evolution of groundwater, the reader is encouraged to consult Alan R. Freeze and John A. Cherry's book *Groundwater* (1979)↗, which can be downloaded as a PDF or read online through The Groundwater Project website.

Precipitation as rain or snow—if unaffected by industrial air pollution—typically has a low TDS concentration; is mildly acidic (pH between ≈5 and 6), and rich in oxygen

(O_2), carbon dioxide (CO_2), sulfur dioxide (SO_2), nitrogen gas (N_2), and argon (Ar). Such oxidizing and mildly acidic water can react relatively quickly with the soils and rocks they infiltrate and saturate. This causes changes in the salinity and structure of the soil and rock while also changing the mineral composition of the water.

The major ion composition of groundwater shows regional changes in dominant anion species (i.e., ions with negative charge) along the flow paths and with increasing age. This is called the *Chebotarev Sequence* (Chebotarev, 1955).

$$HCO_3^- \rightarrow HCO_3^- + SO_4^{2-} \rightarrow SO_4^{2-} + HCO_3^- \rightarrow SO_4^{2-} + Cl^- \rightarrow Cl^- + SO_4^{2-} \rightarrow Cl^-$$

where:

HCO_3^- is bicarbonate (hydrogencarbonate),

SO_4^{2-} is sulfate, and

Cl^- is chlorine.

In large sedimentary basins, the Chebotarev Sequence is correlated with the recharge, midline, and discharge areas of the basin (Domenico, 1972) and shows the following characteristics.

- Recharge Areas are dominated by HCO_3^- and have low TDS. The water is oxidizing and mildly acidic.
- Midline Areas are dominated by SO_4^{2-} and have elevated TDS.
- Discharge Areas are dominated by Cl^- and have high TDS.

The above chemical characteristics of flow systems can vary greatly due to the types of soluble salts encountered along the flow paths. For instance, in areas where anhydrite ($CaSO_4$), gypsum ($CaSO_4 \cdot 2H_2O$), or common salt (NaCl) are encountered in the shallow subsurface, the dominant anions of local flow systems will be SO_4^{2-}or Cl^-, respectively. In the absence of Cl^-, the discharging groundwater will be rich in HCO_3^- or SO_4^{2-} type salts. Soluble minerals are thus transported in increasing concentrations by groundwater from their original source; they can accumulate or be redeposited by groundwater in zones of stagnation such as ponds, lakes, seepage faces, or the vadose zone in shallow soils. They can also accumulate or be redeposited in the subsurface in zones of convergent or divergent flow systems called *hydraulic traps*.

Similar to transportation of dissolved salts, moving groundwater also transports metals (e.g., copper (Cu), lead (Pb), zinc (Zn), uranium (U)) and hydrocarbons (e.g., natural gas, petroleum, condensates). Some of the world's largest metal and hydrocarbon deposits have occurred as the result of mobilization, transportation, and accumulation by groundwater.

In discharge areas, near-surface indications of salts, metals, and hydrocarbons suggest accumulation in subsurface stagnation zones, as not all the mobilized matter gets trapped. Where such indications are encountered, ascending groundwater flow paths form a distinct near-vertical geochemical anomaly called a *geochemical chimney*.

Groundwater temperature is characteristically lower beneath recharge areas where the percolating rain or snow melt is cooler than the ambient soil temperature. As groundwater moves downward toward progressively warmer zones, the water temperature gradually increases; some of this heat is transported toward the discharge area or zone of stagnation. Terrestrial heat increases with depth, so the warmer the discharging groundwater at a spring or lake, the deeper the flow system must be to bring such heat to the surface. Hot springs are typically associated with groundwater that reached great depth or with high terrestrial heat flow, whereas cold springs are commonly the expressions of shallow groundwater flow systems.

Groundwater discharge affects the mechanical stability of soils by liquefying saturated soils and reducing their *shear strength* (i.e., the maximum stress soils can withstand before yielding to shear force). Common geotechnical problems that may occur because of these discharge phenomena include soap holes (localized regions of liquefied clay), quicksands (sand that behaves as a liquid because it is saturated with water), and landslides.

Moisture content and chemistry also determine the vegetation associated with soil conditions (i.e., dry or wet/saline or non-saline. Plants adapted to limited or low water supply—*xerophytes*—are common in recharge areas. Conversely, plants adapted to abundant water supply of low salinity are *phreatophytes*, and those adapted to variable water supply of high salinity are *halophytes*.

Thus, groundwater flow systems (as shown in Figure 17) have a determining and complex role in the distribution of heat, matter, vegetation, and soil conditions—hence the phrase *moving groundwater as a geologic agent* coined by Tóth (1999).

In gravity-driven flow regimes, the range of hydraulic head (i.e., the elevation that water rises to in a pipe open to a discrete point in the subsurface) is limited by the difference in elevation between the recharge and discharge areas. In a hydrostatic system, hydraulic head is constant with depth and is equal to the elevation of the groundwater table above that location. In a gravity driven flow system, in recharge areas hydraulic head is sub-hydrostatic, decreasing with depth, while in discharge areas hydraulic head is super-hydrostatic, increasing with depth.

In flow regimes driven by gravity, pore pressure—the pressure of groundwater held within soil or rock—always increases with depth but the rate of increase varies with location. At the mid-line of a unit basin (Figure 15), flow is horizontal and head does not change with depth. Thus, along the midline, pore pressure increases at a rate known as the *hydrostatic gradient* which is caused by the increasing weight of the continuous, interconnected column of fluid from the water table to depth) in areas with no vertical component of flow.

The maximum pressure in such systems will not exceed the weight of a water column of a height equal to the difference between the maximum water table elevation in the basin and the minimum elevation of the impermeable basement. Tóth's model uses a horizontal base with an elevation of zero for the impermeable basement, thus the maximum pressure head does not exceed the maximum elevation. In a natural gravity driven system in which the bottom of the basin is less than an elevation of zero, the maximum pressure will be higher than the maximum elevation of the water table, but the hydraulic head difference is limited by the range in head at the recharge and discharge locations.

The variation of groundwater pressure with depth in gravity-driven flow systems is defined as *normal*. Any deviation from normal pressure gradients is deemed a *pressure anomaly*. The causes of such anomalies require further evaluation as anomalous pressure gradients can be due to several natural mechanisms and their cumulative effects in complex geological systems. These gradients are grouped into three categories (denoted here with a, b, and c), bearing in mind that water is almost incompressible.

a) Changes in pore volume caused by pore volume expansion due to extensional stress (or relaxation) or reduction of pore space caused by an increase in compressive stress known as compaction.
b) Changes in fluid volume caused by thermal expansion, diagenesis (physical and chemical changes in sediments), or generation of hydrocarbon.
c) Fluid movement and processes related to density differences between fluids (including gases) caused by buoyancy forces, hydraulic gradients, and osmosis.

Extensional stresses acting on the rock framework induce sub-hydrostatic vertical pressure gradients on groundwater, manifesting as a *suction effect* described as an *underpressured system*. In contrast, compaction (lateral or vertical) induces super-hydrostatic gradients and thus are termed *overpressured systems*. Mechanisms in categories (b) and (c) induce over-pressured systems. The pressure distribution with depth in abnormal systems is offset from the normal conditions observed in unstressed, gravity-driven systems, with lower pressures at an equivalent depth in an under-pressured system and higher pressures at an equivalent depth in an over-pressured system.

Fluid flows in anomalous pressure systems, however the flow patterns in these pressure regimes do not necessarily display the hierarchical patterns of gravity-driven flow systems previously described. Under- and over-pressured conditions can be superposed on gravity-driven flow regimes in natural systems. The generation and maintenance of anomalous pressure regimes, as well as the timing, duration, and relative efficiency of anomalous pressure-generating mechanisms is controlled by the geological, geophysical, and geochemical characteristics of a sedimentary basin and its evolutionary history. Exercise 1 provides readers with an opportunity to apply their understanding of gravity-driven flow systems. Exercise 2 provides readers with an opportunity to explore gravity-driven flow systems.

4.7 Groundwater Flow Systems in the Pannonian Basin

Two vertically stacked major groundwater flow regimes are found within the Pannonian Basin: an upper *gravity-driven* flow regime and a lower *overpressured* flow regime (Almási, 2001; Tóth and Almási, 2001). We discuss the plausible driving forces of overpressures below.

4.7.1 Gravity Driven Flow Regime

The gravity-driven flow regime extends to depths ranging from the surface to ≈2,500 m below ground surface; this regime is regionally unconfined in the Nagyalföld Aquifer (Erdélyi, 1976; Almási, 2001). Within the exposed Mesozoic carbonate rocks and Pleistocene volcanic rocks, groundwater flow is also driven by gravity. Within this flow regime are large regional and intermediate groundwater flow systems (1 to 100 km in lateral extent) and myriads of small local flow systems. This regime is recharged by precipitation, with the hills and mountains of the basin acting as recharge areas. The water table elevation across the basin is illustrated in Figure 18 (after Tóth et al, 2010).

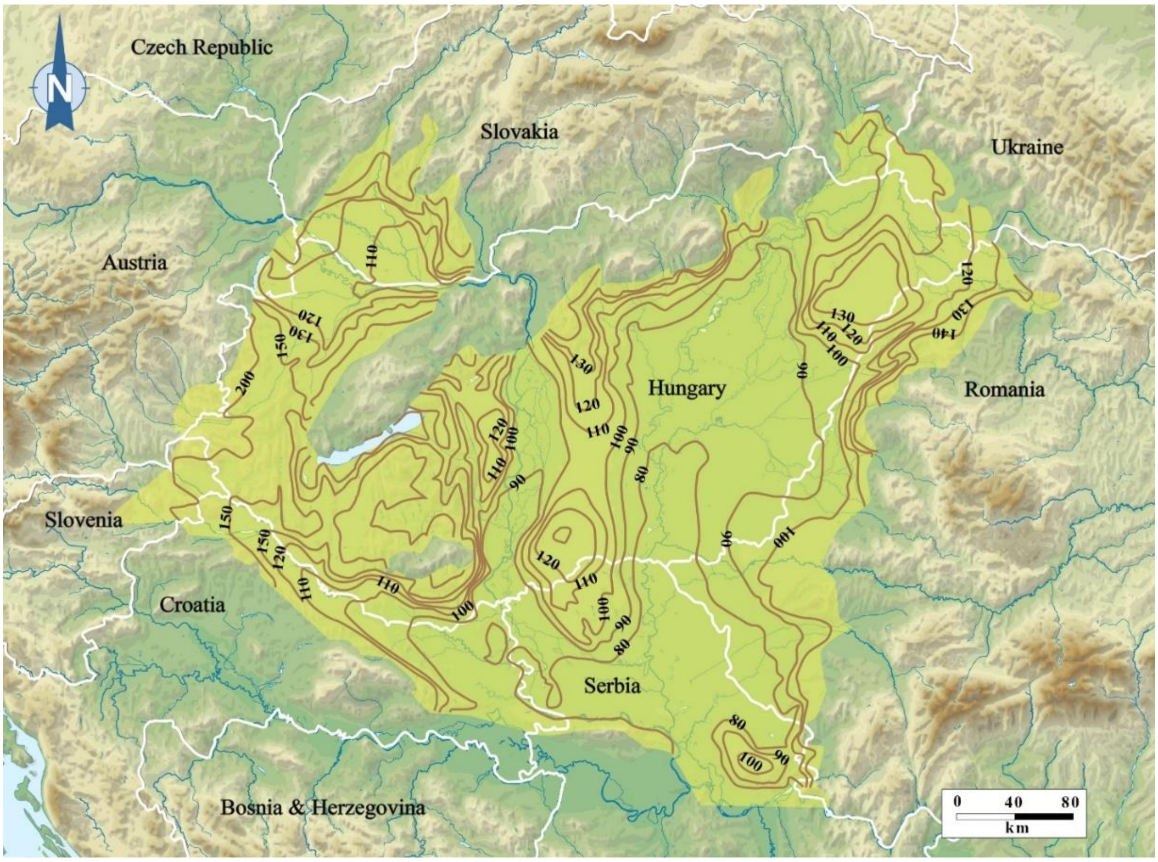


Figure 18 - Water table elevation across the Pannonian Basin in meters above sea level, with a 10 m contour interval (modified after Tóth et al, 2010).

In the hilly areas, pressures increase with depth along slightly sub-hydrostatic dynamic gradient in conjunction with decreasing hydraulic head with depth (Figure 17; Tóth, 2009). Low-lying areas are characterized by a shallow water table, typically near or within 3 m below the ground surface. These are discharge areas where artesian conditions prevail and pressures increase with depth along super-hydrostatic dynamic gradients in conjunction with increasing hydraulic head with depth (Figure 17). Groundwater discharge features can be observed as groundwater-fed wetlands, springs, flowing wells, and gas seeps. Groundwater-fed wetlands were usually perennial or permanent wetlands prior to the water regulations introduced in 1846, as shown in Figure 3. Seasonal surface runoff from the surrounding mountains greatly influenced the lateral extent of these wetlands, resulting in frequent floods. Flowing wells are common in the low-lying areas, where the ground elevation is below 110 masl. The deeper the well drilled in such areas, the higher the likelihood of encountering flowing conditions. Thus, for centuries the Pannonian Basin has been considered an artesian basin.

The surface pattern of ecosystems (especially flora) is largely determined by hydrogeological conditions and the rate of subsurface recharge as described in *4.5 Groundwater Flow Systems* of this book. We can infer from surface vegetation whether we are in a discharge or recharge area of the groundwater flow system. The recharge areas are characterized by drought-tolerant plant communities (xerophytes), while the discharge areas are characterized by water-tolerant plant communities (phreatophytes or halophytes). Near a regional discharge area, where water arrives with relatively low fluxes from long distances, salt-tolerant plants are typical due to higher salt concentrations resulting from evaporation, while wetland plant communities are typically found in the vicinity of areas with abundant water recharge.

A good example of this pattern of distribution of vegetation types are the dune slopes of the Danube-Tisza Interfluve that usually feature small sand hills alternating with depressions as shown in the model presented in Figure 19. Pannonian sand, steppe vegetation is found on the gentle slopes of the sand hills. Small depressions on the side of the sand hills are often local discharge areas within a regional recharge or midline zone, also known as a *recharge slough*, where wet meadows develop. In a regional or intermediate discharge area of lowest relative elevation, fen or bog vegetation occurs, an environment that is alkaline (pH ranging from ≈7.5 to 8.5) and commonly associated with high salinity. As water and soil salinity increases in discharge areas, fens and bogs are replaced by alkali meadows. In the lowest areas, salt marshes—and sometimes alkali lakes—can be found (Figure 19) (Margóczi et al., 2007).

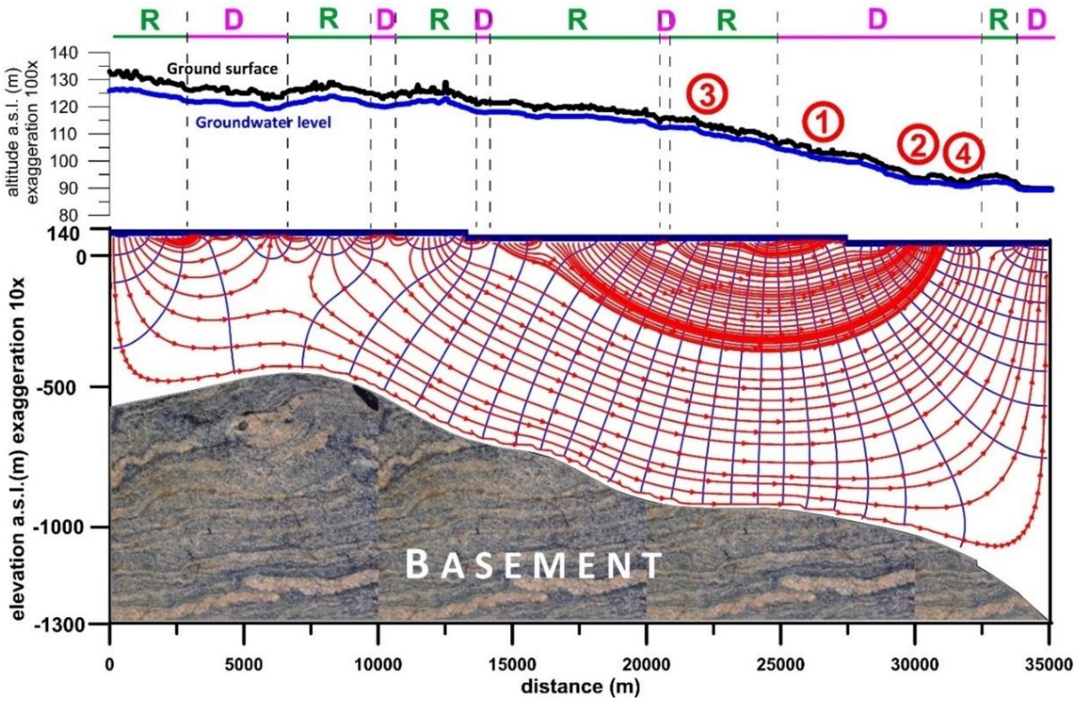


Figure 19 - Model of hydraulic flow system with exaggerated surface and groundwater-level line (blue: equipotential lines; red: flow lines). The numbers show the location of different vegetation types:

(1) fen or bog;
(2) wet meadow;
(3) Pannonic sand steppe; and
(4) Pannonic salt vegetation.

Figure 20 provides photos of the vegetation types found in each setting (after Margóczi et al., 2007).

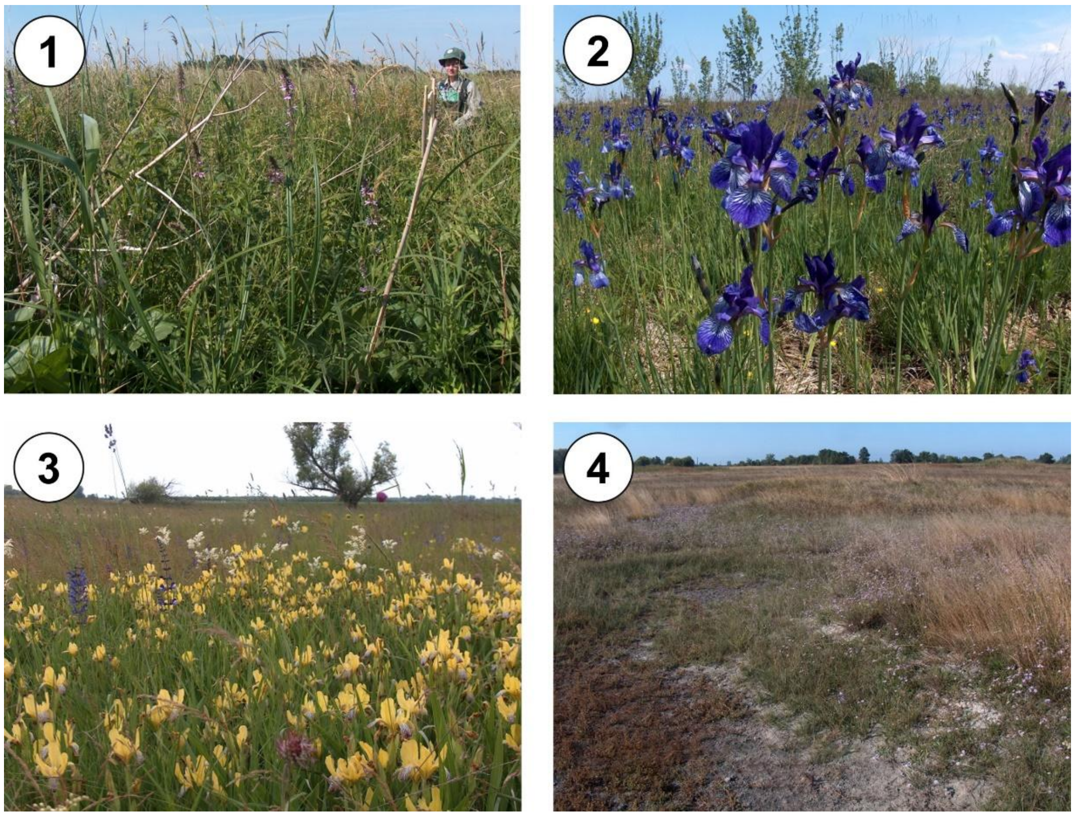


Figure 20 - Natural vegetation types of the Pannonian Forest steppe: 1) fen/bog; 2) wet meadow; 3) Pannonic sand steppe; and 4) Pannonic salt vegetation (after Margóczi et al., 2007).

Drinking water is produced mainly from the upper part of the Nagyalföld Aquifer (Pleistocene age). Thermal water is extracted from the deeper Zagyva and Újfalui Formations of this aquifer.

To a large extent, sediment types determine the freshwater yields of shallow aquifers. Shallow aquifers within the *phreatic zone* (the zone of saturation) are predominantly fine sands and wells have modest yields on the order of 1 to 50 L/min (Liters per minute), whereas wells in coarse sand and gravel aquifers in the same zone yield 100s to over 1,000 L/min.

Water table fluctuations are greatly influenced by seasonal meteoric recharge; however, their magnitude is also controlled by topography and the porosity of aquifers. In coarse sand and gravel aquifers of high porosity in low-lying areas, annual water table fluctuations are on the order of tens of centimeters, whereas in medium-fine sand and silty aquifers, annual fluctuations of up to 2 m have been observed in elevated areas. Sand and gravel aquifers from 400 m to 2,500 m depth have well yields often exceeding 100 L/min and yields of 1,500 L/min are common. Many of the wells produce thermal water.

Karst aquifers in the hills and mountains within the basin are also prolific water sources for both potable and thermal water supplies. Since the 1980s, over 80 percent of drinking water has been supplied by groundwater from a combination of the upper 400 meters of the sedimentary basin fill and the karst aquifers.

Exercise 3↴ provides readers with an opportunity to apply their understanding of gravity-driven flow systems in the Pannonian Basin.

4.7.2 Overpressured Flow Regime

The overpressured flow regime is characterized by excess pressures on the order of 10 to 40 MPa (megapascals) above local hydrostatic pressure, which is equivalent to a 1,000 to 4,000 m water column above hydrostatic conditions (Figure 21). The maximum pore pressure generated by gravity-driven flow in the Pannonian Basin does not exceed 0.5 MPa. The overpressured regime is confined to the Algyő Aquitard, Szolnok Aquifer, Endrőd Aquitard, and the Paleozoic and Mesozoic basement rocks across the Pannonian Basin. The transition zone or boundary between the two pressure regimes is not consistently associated with any regional hydrostratigraphic unit or specific depth in the basin. Local variation in permeability due to lithologic heterogeneity (variation in rock texture and structure) and fracture zones are believed to control the maintenance and dissipation of pressure from the overpressured zone and hydraulic communication between the two vertically stacked flow systems of the different pressure regimes. The vertical transition zones between the two pressure regimes are gradual within basement depressions (dissipation across a 400 to 800 m thick zone), and abrupt above basement highs (dissipation across a 50 to 300 m thick zone).

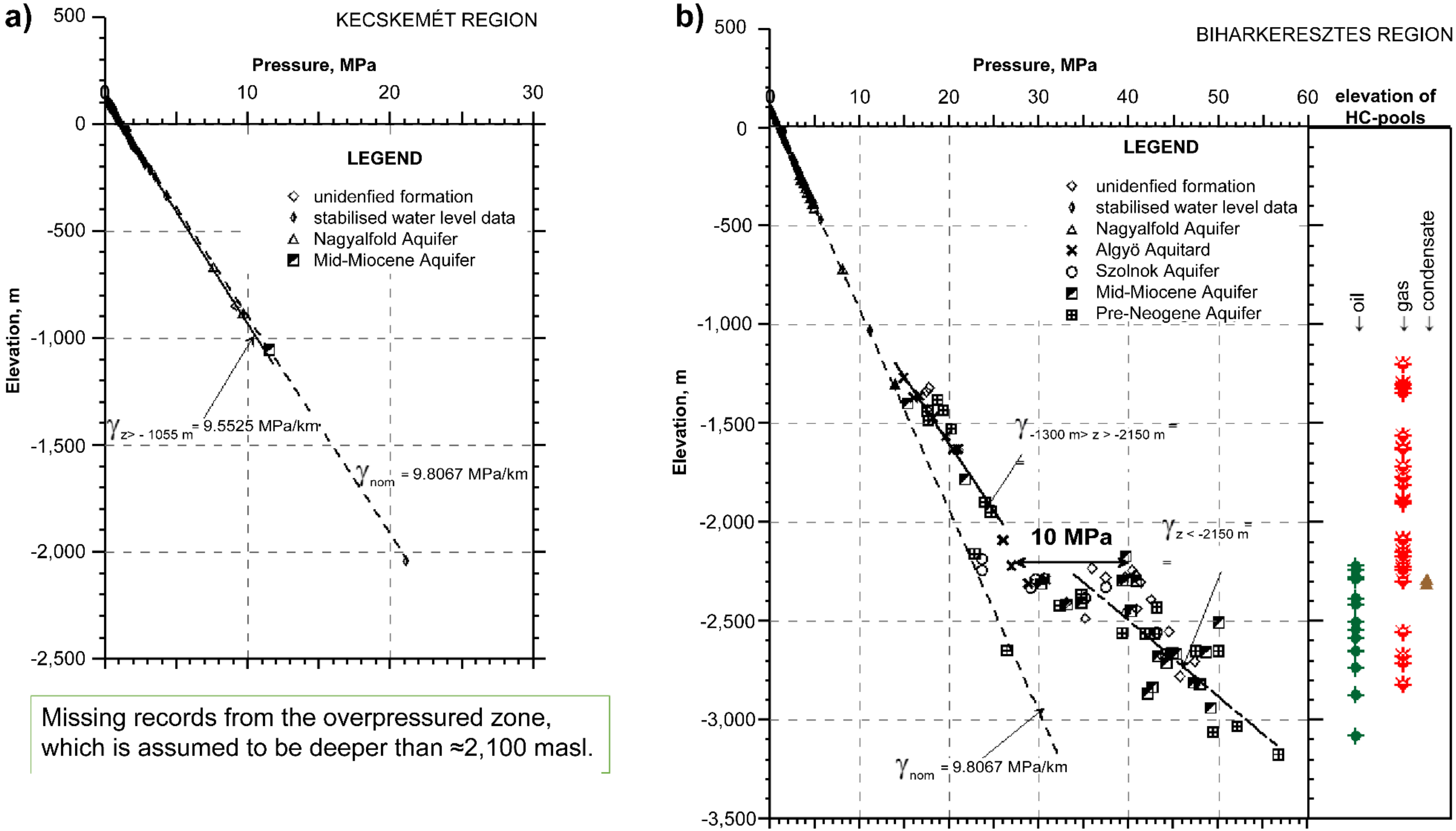


Figure 21 - Pressure elevation profiles: a) slightly sub-hydrostatic dynamic pressures in a recharge area (Kecskemét Region of central Hungary); and b) abnormally high super-hydrostatic pressures in a discharge area (Biharkeresztes Region on the eastern border of Hungary) suggesting mechanisms such as tectonic compression, vertical compaction, aquathermal pressuring, diagenesis, hydrocarbon generation, buoyancy forces, or osmosis may be active in the area (modified after Almási, 2001).

In Figure 21, the hydrostatic gradient is shown by the dashed line as γ_{nom} = 9.8067 MPa/km. In the gravity-driven flow regime, pressure measurements that plot below the local hydrostatic line indicate recharge conditions (downward flow along a mean dynamic gradient of 9.555 MPa/km). Hydrostatic values may indicate lateral flow or no-flow conditions, while values slightly above the hydrostatic line indicate discharge conditions or upward flow. Pressure gradients exceeding 10 MPa/km indicate the presence of an overpressured zone where pressures are generated by non-gravitational mechanisms (e.g., tectonic compression, vertical compaction, aquathermal pressuring, diagenesis, hydrocarbon generation, buoyancy forces, and osmosis).

Overpressures are ubiquitous throughout the Pannonian Basin, within and beneath the Algyő Aquitard. The regional occurrence of the overpressured regime reflects hydrodynamic disequilibrium, which must be due to regionally-effective geologic processes or energy sources that were, or are, active in the basin. The non-uniform distribution of overpressures (i.e., overpressures are observed everywhere, but at different depths and with variable magnitude) may be explained by differences in permeability at regional and local scales, by the contribution of locally-effective energy sources and sinks, and by the spatial and temporal variation of pressure-generating and dissipating factors (such as osmosis, diagenesis, tectonic compression, hydrocarbon generation). Maintenance of anomalous pressures depends on the lifetime and spatial distribution of the pressure-energy sources and the hydraulic conductivity of the rock formations.

A plausible explanation for the generation, magnitude, and maintenance of overpressures within the Pannonian Basin is compaction due to lateral compression induced by recent and ongoing tectonic forces (*neotectonics*). Recent stress field measurements provide clear evidence for a present-day compressive regime in the basin. Overpressures observed both in the rigid basement rocks and the partially-consolidated sedimentary rocks induce upward flow within the lower part of the basin. Lateral flow components are directed toward the interior of the deep sub-basins.

4.8 Hydrochemistry

Groundwater mineralization is influenced by local geology and groundwater flow conditions. Within the Pannonian Basin, the total dissolved solids concentration (TDS) ranges from hundreds to a maximum of 55,000 mg/L (milligrams per liter). Most water-supply wells produce water with low salinity (TDS < 500 mg/L) at depths ranging from 10 to 1,000 m. Elevated salinity is common in discharge areas (wetlands) and karst aquifers where water salinity exceeds 3,500 mg/L. Soil salinization is commonly observed in local discharge areas, as shown in Figure 22.

Figure 22 - An example of soil salinization in the Great Hungarian Plain.

In recharge areas of relatively high topographic elevation, groundwaters are commonly of the calcium/magnesium-bicarbonate type, whereas sodium-bicarbonate type waters predominant in low-lying discharge areas. Transition from calcium/magnesium to sodium-bicarbonate type waters is continuous along regional flow paths from the Duna-Tisza Interfluve area toward the low-lying center of the Great Hungarian Plain as illustrated in Figure 23 (Mádl-Szőnyi and Tóth, 2009).

Waters of the calcium/magnesium-bicarbonate type dominate the karst aquifers, with TDS values ranging from about 300 to 2500 mg/L. Locally-elevated sulphate concentrations are often associated with gypsum or anhydrite. Naturally-elevated arsenic, ammonium, iron, and phosphate concentrations are common in the middle of the Great Hungarian Plain, northeastern Serbia, and the Dráva Basin (Varsányi et al., 2006; Stauder 2007). In some places, these concentrations are such a problem that they block the supply of potable water. The highest value of arsenic content in Vojvodina (320 µg/L) was measured in Taras, Serbia, along the Tisza River (Stanic, 2018).

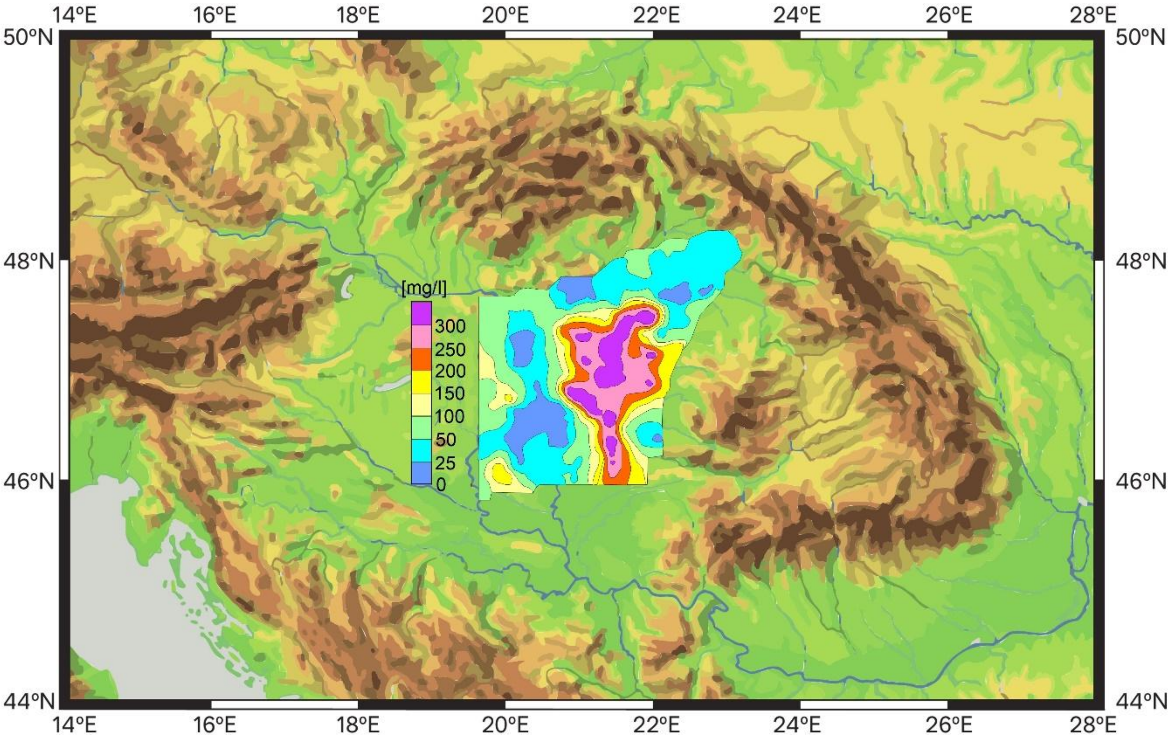


Figure 23 - Sodium (Na) content of groundwater exploited from early Pleistocene-age sediments of the Nagyalföld Aquifer (based on Deák, 2013).

4.9 Age of Groundwater

Knowing the age of groundwater is critical for assessing the recharge potential of aquifers, sustainability of groundwater exploitation, velocity of groundwater flow, and contaminant migration. From the distribution of groundwater age in a large basin, one can infer several characteristics of a flow regime such as hydraulic conductivity, flow rate, transit time of water movement across strata, and the source of the water, as well as the likely age of the pressure regime encountered in a geological formation (Figure 24).

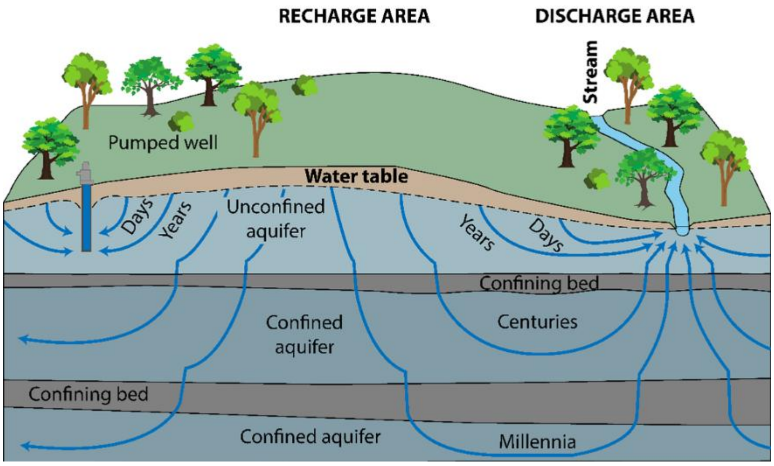


Figure 24 - Probable age of groundwater according to flow system type and depth (after Winter et al., 1998).

Groundwater age-dating methods have been reviewed by Cook (2020) (isotopes and other natural or inherent tracers). Tritium, ^{14}C, $\delta^{18}O$, and deuterium ($\delta\,^{2}H$) age-dating methods have been applied in the Great Hungarian Plain of the Pannonian Basin since the 1990s (Palcsu et al., 2017). Helium analysis, based on the $^{3}He/\,^{4}He$ ratio, was also used to evaluate deep recharge from the lower part of the crust or upper mantle (Deák, 2013). Water samples were collected from the upper 1,000 m thick zone of the drinking water-bearing Nagyalföld Aquifer. The sediments from the sampled aquifer were deposited in the early Pleistocene (approximately 1.8 Ma ago).

The aquifers can be considered as a continental paleoclimate archive. For example, the relationship between precipitation and groundwater $\delta^{18}O$ and $\delta\,^{2}H$ values, together with noble gas measurements, provide insights into the paleoclimatic conditions at the time of recharge. The amounts of inert gases are suitable indicators of the temperature at which groundwater recharge occurred (Varsányi et al., 2011).

Varsányi and others (2011) investigated the isotope and noble gas data at a study area that covers about 3,200 km^2 situated in the southeastern part of Hungary in the Pannonian Basin; the wells studied are in a Pleistocene aquifer in an area between the Rivers Danube and Tisza and the southern Tisza region (where the vegetation investigation shown in Figure 18 was carried out). The depth of the wells varies from 9 to 741 m, generally following the dip and thickness of the Pleistocene layers (Figure 25). According to their calculations, the difference between the late glacial minimum temperature and the Holocene temperature is 9.1 ± 0.8 °C. Knowing these data, it is possible to determine where along the flow path the glacial- and Holocene-infiltrated waters are located (Figure 25). These results also indicate that the sediments are generally much older than the water flowing through them.

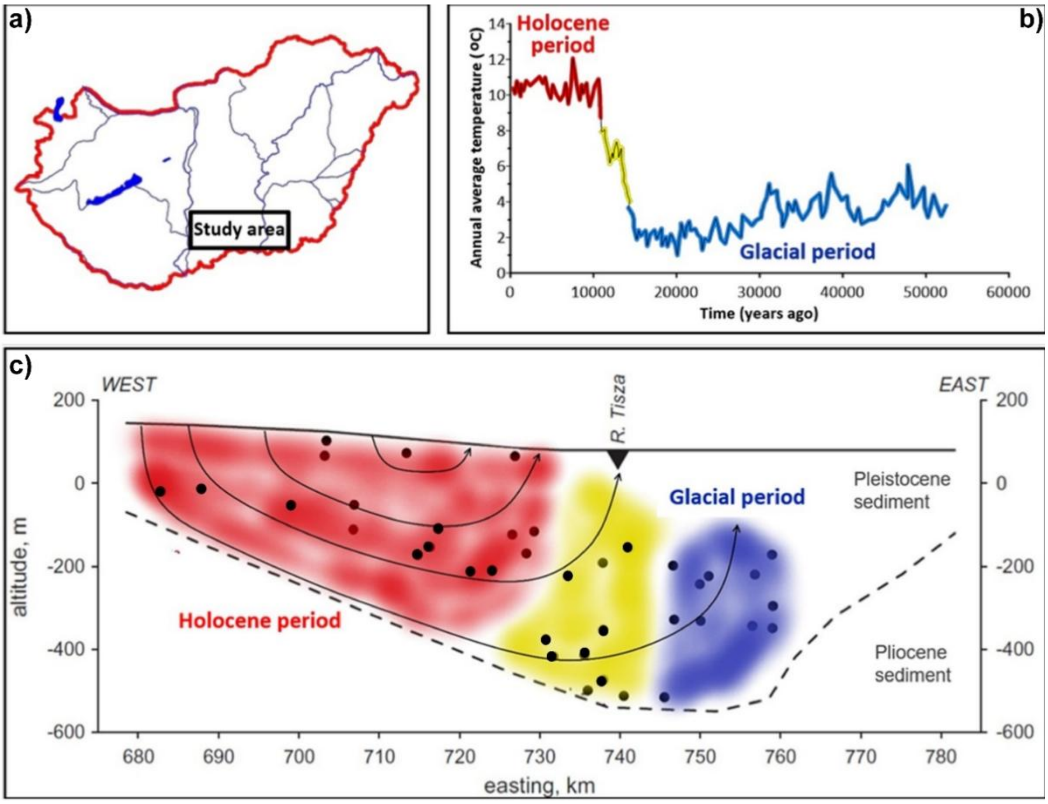


Figure 25 - a) Location of the isotope-noble gas investigation. For the group of data from the central portion of the study area: b) recharged precipitation temperature by noble gas versus age of water by 14C; and c) W-E cross-section with flow direction and the bottom of wells indicated by black dots (after Varsányi et al., 2011).

^{14}C age-dating results by Deák (2013) as shown in Figure 26 illustrate relatively young water less than 10,000 years old lies beneath the recharge areas and progressively older water (up to 40,000 years) is found toward the low-lying discharge areas. The age contours in this depth range replicate the pattern of horizontal hydraulic head distribution, which indicates an excellent correlation with gravity-driven groundwater flow in this domain.

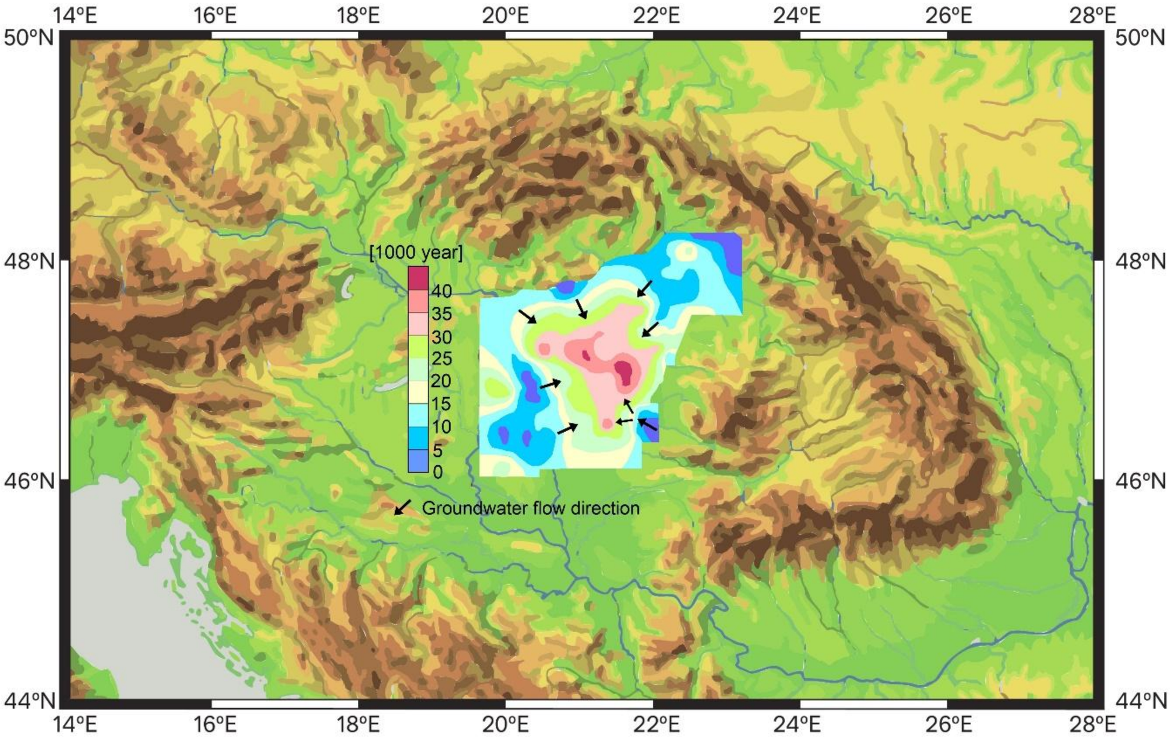


Figure 26 - Carbon (^{14}C) age of groundwater exploited from Early Pleistocene age sediments of the Nagyalföld (based on Deák, 2013).

Seepage rates were calculated for both recharge and discharge areas based on ^{14}C ages. Under the Duna-Tisza Interfluve recharge area, the amount of net groundwater recharge from precipitation of all forms ranges from 22 to 53 mm/year, or approximately 5 to 10 percent of annual precipitation. The same isotopic measurement methods indicated the rate of natural discharge was on the order of -19 to -45 mm/year within the low-lying areas of the Great Hungarian Plain. The apparent water imbalance is due to multiple factors such as the redistribution of recharge to the west of the Duna-Tisza Interfluve area, additional recharge of the low-lying areas from the foothills of the Carpathians to the north, and large-scale groundwater diversion by waterworks within the basin.

Climatic conditions of recharge were inferred from $\delta^{18}O$ and deuterium ($\delta\,^{2}H$) analyses by Deák (2013). It turned out that relatively high $\delta^{18}O/\delta^{16}O$ ratios of -8 to -10 ‰ SMOW (standard mean ocean water)—typical of recent climatic conditions—were found under recharge areas; while progressively lower values of -11 to -14 ‰ SMOW known to be from the Ice Age were found in discharge areas.

5 Groundwater Use

Until the middle of the nineteenth century, the domestic water supply for the Pannonian Basin was provided by dug wells and surface water. Use of groundwater in the Great Hungarian Plain by deep wells was introduced by Béla Zsigmondy in the 1850s. He drilled up to 400 m deep drinking water wells, and up to 1,000 m deep thermal water wells.

The number of wells grew at a rapid rate. By 1900, Hungary had 2,400 artesian wells, and their number had increased tenfold by 1940. There are currently more than 60,000 water wells on record. Groundwater production has gradually increased, currently producing 1,018 million m^3/year; about 70 percent of this amount is used by water supply companies for domestic purposes. Water well information from outside Hungary was not readily available to the authors at the time this book was prepared.

The most abundant drinking water aquifers are found in Quaternary sedimentary deposits, while in the hilly or mountainous areas drinking water is supplied by karst aquifers (mainly carbonates), fractured volcanic and volcanoclastic aquifers, and to a lesser degree from other types of fractured rocks. Areal distribution of these aquifer types is illustrated in Figure 27 (Liebe, 2002; Nistor, 2019).

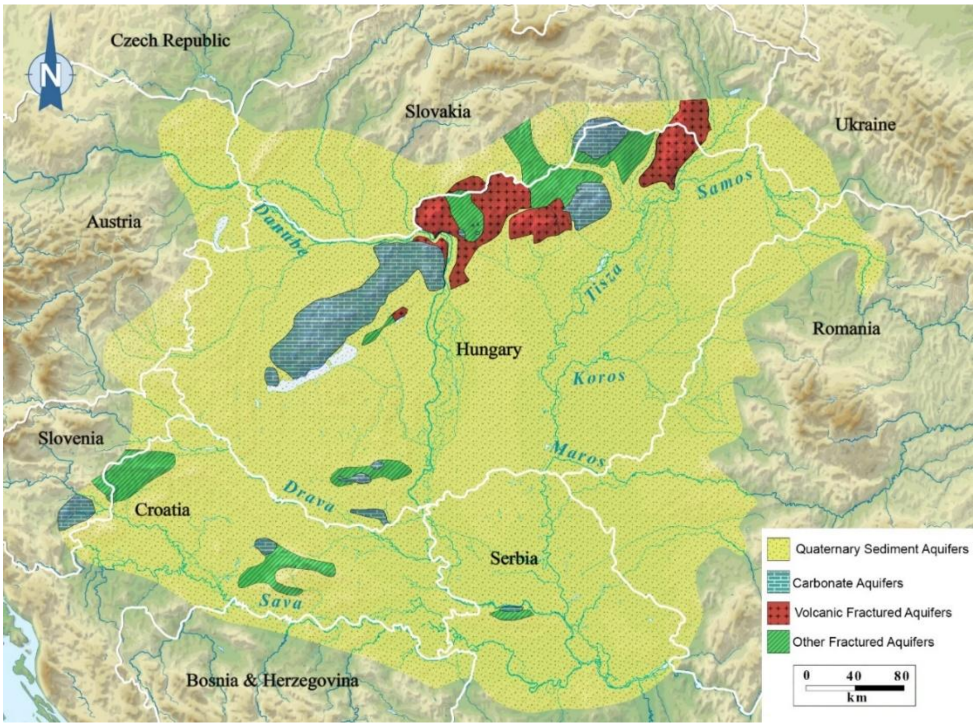


Figure 27 - Aquifer types used for drinking water in the Pannonian Basin (modified after Liebe, 2002 and Nistor, 2019).

In Hungary, groundwater production in 1990 was approximately 40 percent higher than at present time (Figure 28). The decrease is a result of significant increases in water allocation prices as an incentive to conserve water by encouraging responsible consumption.

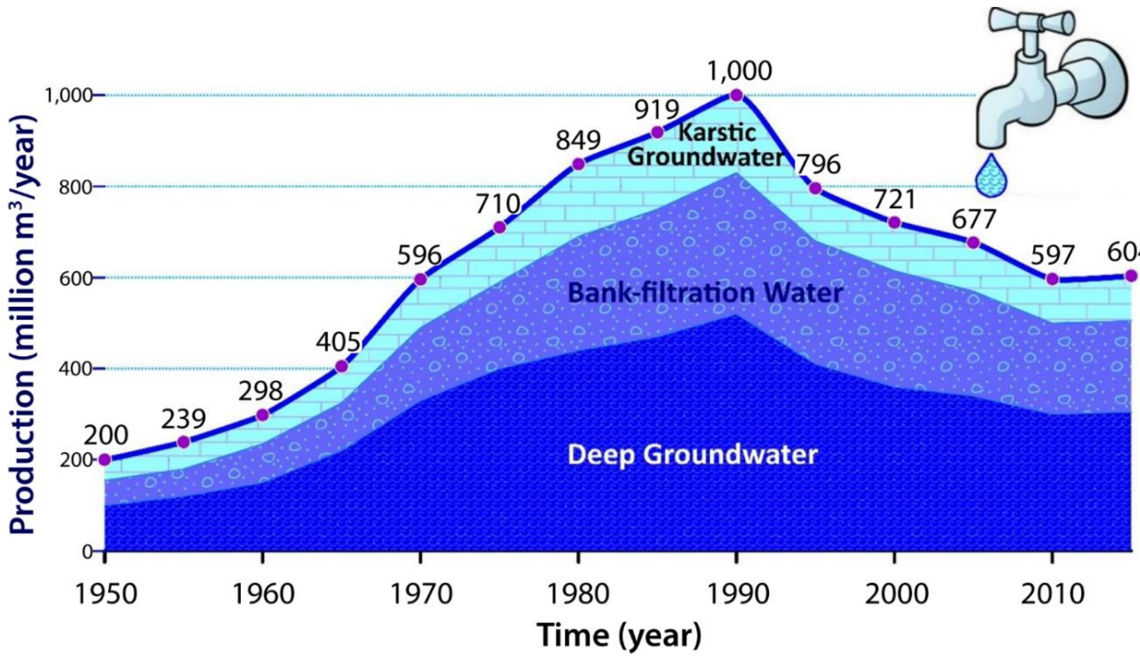


Figure 28 - Annual groundwater abstraction by water supply entities in Hungary (data source: Government of Hungary, General Directorate of Water management).

In Hungary, about 50 percent of all groundwater produced comes from wells installed deeper than 20 m bgs (below ground surface), up to a maximum depth of 3,000 m, with approximately 35 percent from shallow riverbank infiltration water, and 15 percent from karstic aquifers. Surface water utilization from lakes and rivers for drinking water is negligible. Unfortunately, similar records are unavailable from other countries overlying the Pannonian Basin.

For the Pannonian Basin, data are available from the entire Danube River Basin where over 59 million people—72 percent of the total population—access their drinking water from groundwater. When more water is used than can be replaced by nature groundwater is extremely vulnerable to over-production (ICPDR, 2021).

The groundwater resources of the Pannonian Basin are a valuable treasure, but the amount that can be extracted is constrained by variable natural recharge. As pumping progresses, more and more layers connect to supply water through the well, inducing artificial cross-formational flow as demonstrated by the experiments of Neuman and Witherspoon (1972). This means that leakage between layers becomes more significant during production. A good example of this is the northeastern part of the Great Hungarian Plain (Debrecen), where about half of the water pumped from wells screened within the lower Pleistocene layer between ~130 to 180 m comes from downward vertical leakage through aquitards, draining the shallow groundwater-bearing zones. This induced water table declines on the order of 5 to 6 m between 1950 and 1990.

5.1 Transboundary Aquifers – Danube River Basin

The Pannonian Basin is an integral part of the larger scale Danube River Basin. The Danube and its tributaries, lakes, and groundwater form the Danube River Basin District (DRBD). The DRBD is the most international river basin in the world, covering the territories of 19 countries.

Human activities such as agriculture, transport, energy production, and urban development exert pressures on the water environment. These pressures need to be assessed as part of sustainable river basin management and for decisions on measures to address and reduce these pressures. However, protecting and improving the waters and environment of the Danube River Basin requires transboundary cooperation; thus, the countries sharing the Danube River Basin agreed to work jointly toward sustainable management of water resources. The Danube River Protection Convention, signed in 1994, provides the legal framework for cooperation on water issues within the Danube Basin (ICPDR, 2021).

The *quantitative status* of transboundary aquifers is assessed according to Guidance Document No. 18 (EC, 2009) per the Water Framework Directive 2000/60/EC of the European Commission (EC, 2000). Thus, the status of transboundary aquifers is determined quantitatively by the following variables:

- groundwater availability versus groundwater abstraction;
- interactions between groundwater and surface water influenced by anthropogenic effects that may change water level and water quality;
- interactions between groundwater and terrestrial ecosystems; and
- saline intrusions in coastal aquifers or groundwater quality changes from alterations of natural flow systems due to long-term water production.

Figure 29 shows quantitative statuses within the DRBD. Good quantitative status is achieved when “The level of groundwater in the groundwater body is such that the available groundwater resource is not exceeded by the long-term annual average rate of abstraction” (Guidance Document No. 18, Section 5.1). The quantitative status of these aquifers is deemed to be failing or poor if one or more of the above variables is not satisfied and when confidence in all four variables combined is medium or low.

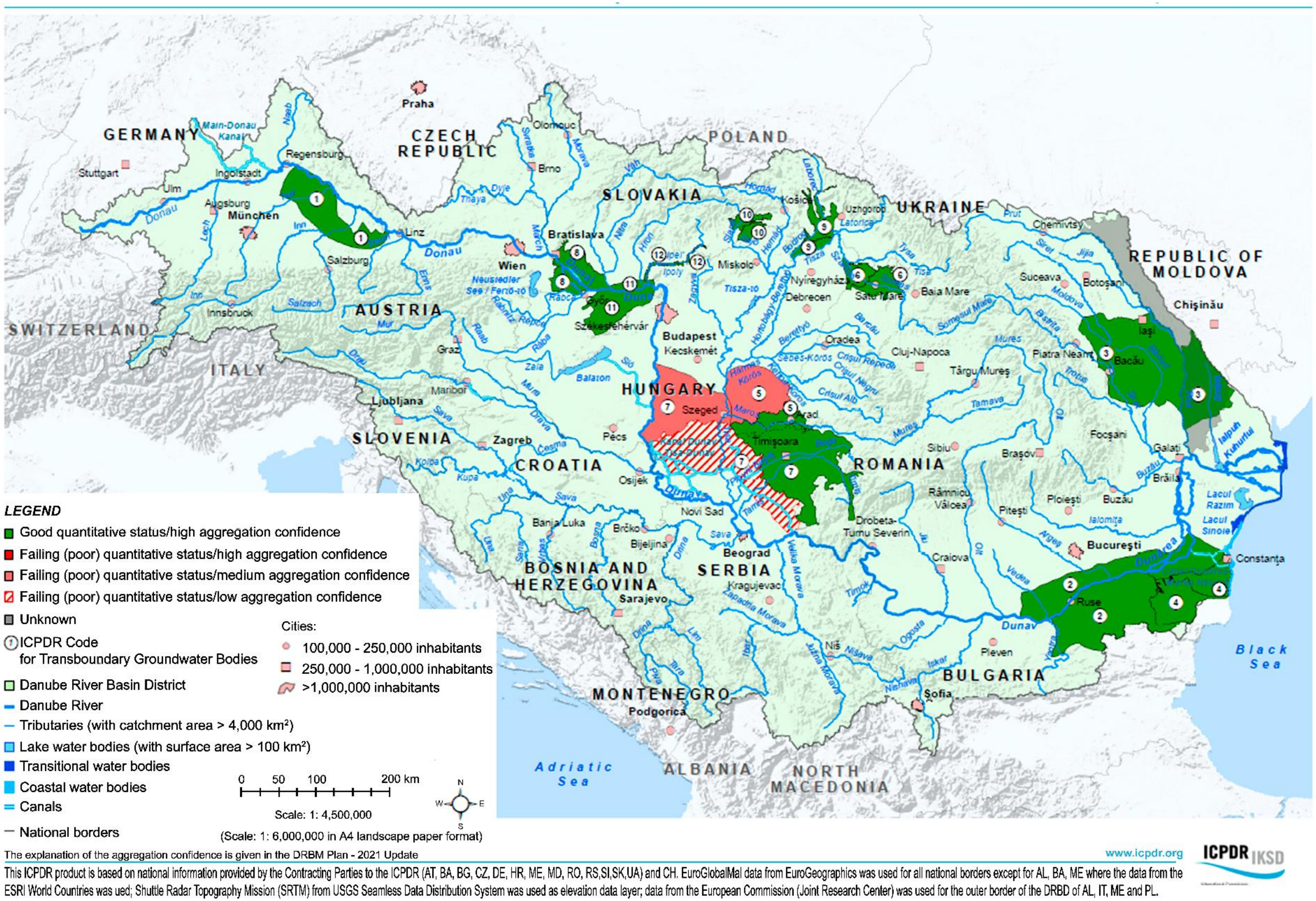


Figure 29 - Quantitative status of groundwater bodies of Danube River Basin-wide importance (ICPDR, 2021).

As essential sources of drinking water and renewable energy, groundwater and thermal water are considered natural treasures in the Pannonian Basin. While thermal water is used for district heating and for medicinal and recreational purposes, industry and agriculture rely heavily on groundwater. Additionally, the Pannonian Basin has been a target for primary petroleum exploration since the 1920s when several gas, oil, and condensate fields were discovered. Extensive groundwater and petroleum exploration and exploitation—spanning over 150 years of recent history—has led to acquiring extraordinary amounts of geological, geophysical, and hydrogeological data. As a *transboundary basin* shared by nine countries, each relying on its water and petroleum resources to varying degrees, the Pannonian Basin is one of the most studied areas in Europe.

The abundance of hot springs with temperatures exceeding 30 °C degrees make the Pannonian Basin uniquely interesting, with thousands of known hot springs and thermal wells with temperatures up to 150 °C. The Pannonian Basin is thus one of the top geothermal anomalies in the world without active volcanoes, allowing its inhabitants direct and indirect benefits due to heat transport by moving groundwater.

5.2 International Initiatives for Groundwater Protection

New legislation was created in all countries in and around the Pannonian Basin for protected areas and banned activities that contribute to water pollution. Between 2012 and 2018, Romania implemented several water treatment projects including new sewage systems and manure storage facilities, and increased the number of residential areas connected to wastewater treatment plants. Slovakia and Hungary also have their own initiatives; the number of inhabitants connected to sewerage networks has increased by 7 percent and 5 percent, respectively, in the same period in these countries. However, significant improvements are still needed in Serbia and Ukraine in this area (ICPDR, 2021).

6 Geothermal Characteristics of the Pannonian Basin

The Pannonian Basin is well known for its geothermal anomalies. The numerous thermal springs in the region are natural indicators of high geothermal gradients and heat flow in this basin (Lorberer, 2003). Large thermal water reserves are stored in the Neogene sediments and Mesozoic carbonate rocks (Figure 30).

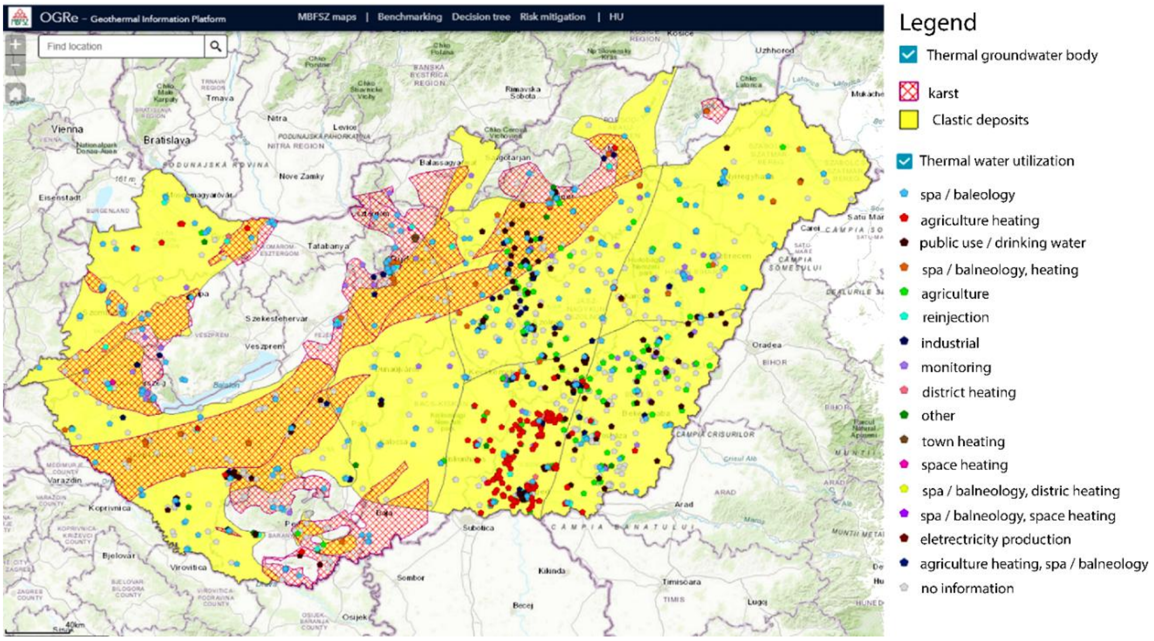


Figure 30 - Thermal water aquifers and utilization in Hungary (source: https://map.mbfsz.gov.hu/ogre_en/↗).

The surface heat flow in the Pannonian Basin generally exceeds 83 mW/m^{2}I ranging between 100 and 130 mW/m^2, whereas in surrounding areas surface heat flow is 40 to 60 mW/m^2 (Dövényi and Horváth, 1988). The geothermal gradients commonly reach 50 to 60 ^{o}C/km—almost double the value of the average continental thermal gradient of (30 ^{o}C/km (Szanyi and Kovács, 2010).

The most significant heat source in the Pannonian Basin is related to the thin (~26 km) continental crust, the upwelling of the hot asthenosphere, and mantle diapirism (Figure 31). A diapir is a less dense body of rock uplifted by buoyant isostatic forces through more dense rock (Ernst, 2014).

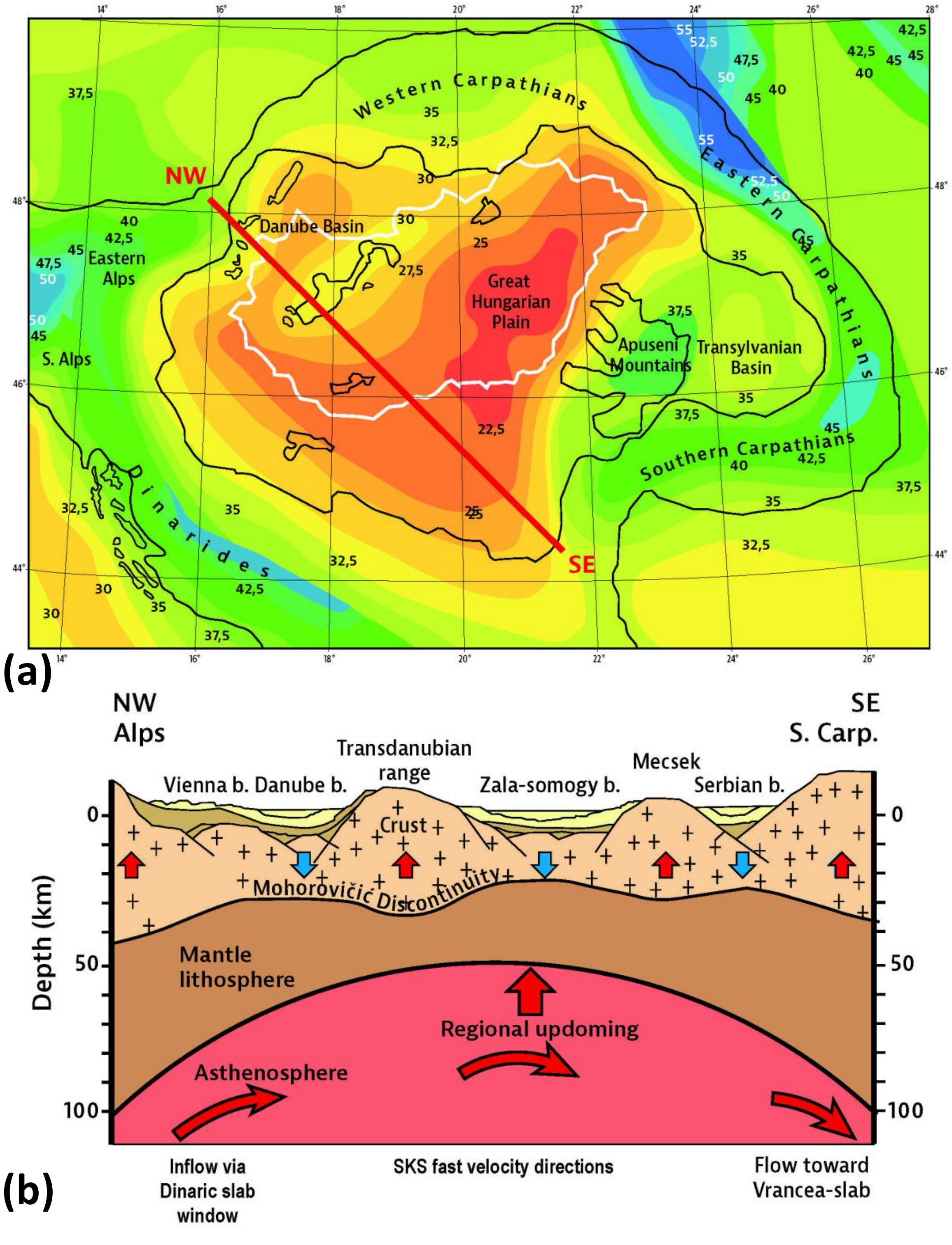


Figure 31 - Crustal thickness of the Pannonian Basin and surrounding regions: a) contour map of crustal thickness with a 2.5-kilometer contour interval—warm colors indicate thinner and cool colors thicker crust; b) sketch of the neotectonic mechanism (rifting) that caused the crustal thinning along the line indicated in (a) (modified from Horváth et al., 2015)..

Radioactive heat sources within the Neogene clastic sedimentary unit and the underlying basement are restricted to a few small areas; their regional significance is considered negligible. In the northeastern part of Hungary, the observed high heat flow is attributed to volcanic activity during the Pliocene. The thick Neogene and Quaternary sediments have a low thermal conductivity. Their rapid deposition resulted in heat flow reduction by up to 20 percent in the western part of the basin, and by up to 30 percent in the southeastern part of the Pannonian Basin.

Groundwater temperatures reach 120 ^{o}C in the clastic aquifers at depths of 2,200 m in Makó Through, Békés Basin, and Dráva Depression areas that are labeled in Figure 2. Temperatures in the older carbonate aquifers exceed 200 ^{o}C at depths greater than 4,000 m in some locales. These conditions are favorable to establishment of medium and high enthalpy geothermal systems. Based on the temperature of the natural fluid (groundwater), geothermal resources can be classified as of high-enthalpy (T >150 °C), medium-enthalpy (T = 90–150 °C) and low-enthalpy (T <90 °C).

The effects of groundwater flow on the distribution of temperature and heat flow has been studied extensively in the Pannonian Basin (e.g., Dövényi and Horváth, 1988; Lenkey, 1999). Advective heat transport is prevalent in areas of relatively high groundwater flow rates, such as karstic aquifers and in the vicinity of fracture zones. Conductive heat transport is prevalent in zones of relatively sluggish flow rates due to either low hydraulic gradients and high permeability, or low permeability and high hydraulic gradients. This is common in the deeper parts of the basin, whether the pressure regime is gravitational or overpressured.

6.1 Geothermal Energy Utilization

The first documented use of geothermal waters in the Pannonian Basin dates to Roman times. Aquincum (now part of Budapest) became the capital of the Pannonian province, where the hot springs were used for heating and bathing. About 1,000 years later in 1178, the Knights of Malta built a bath on the site of Császár Bath (Budapest) to recuperate those returning from the Crusades. In the sixteenth century, the Turks brought with them a sophisticated bathing culture, and built nine Turkish baths in Buda.

From the second half of the nineteenth century, during the period of the Austro-Hungarian Monarchy, a vast majority of the famous medicinal thermal water resources were explored such as Balatonfüred, Harkány, Széchenyi fürdő, Hévíz, and Hajdúszoboszló in Hungary; Pöstyén (Piešťany) in Slovakia; Félixfürdő (Băile Felix) and Herkulesfürdő (Băile Herculane) in Romania; Magyarkanizsa (Kanjiža) in Serbia; and Lipik in Croatia (Figure 32). The first international balneological congress was organized in Budapest in 1936. The balneological use of geothermal energy has increased significantly in all countries of the region, especially in Hungary, where 162 thermal baths are currently in operation and the number of annual visitors exceeds 30 million.

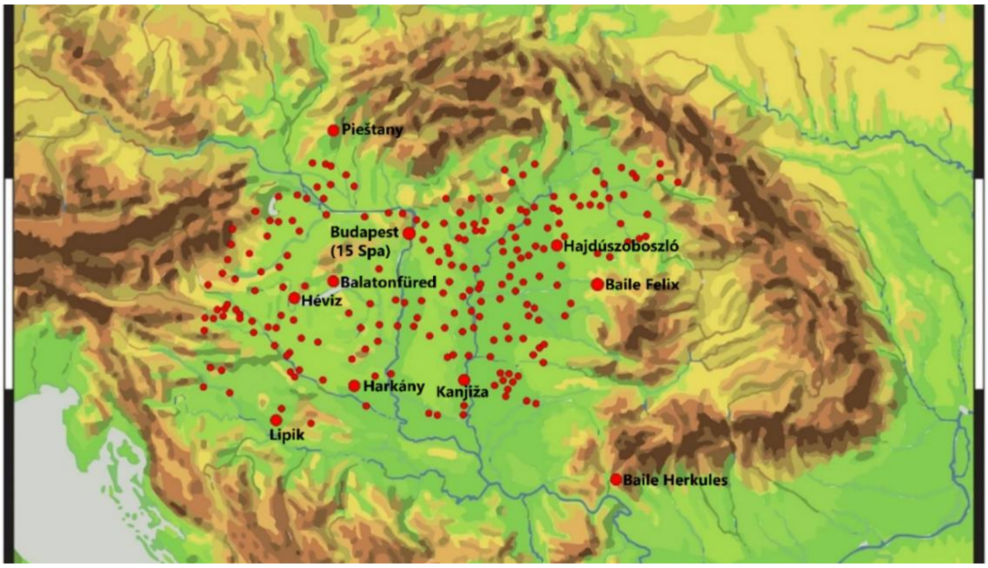


Figure 32 - Locations of thermal spas in the Pannonian Basin. (based on Horváth et al., 2015)

The rapidly growing number of thermal-water wells was partly due to intensive hydrocarbon exploration. A growing number of oil and gas wells were transformed into water wells that produced high-temperature groundwater. These well fields became *thermal water centers* supporting both agriculture and district heating networks. The best-known thermal water center is near Szentes, Hungary, where 60 hectares (600,000 m^2) of greenhouses are heated solely by thermal water.

The most effective method for geothermal energy use is multi-stage cascade utilization. Figure 33 shows an idealized multi-stage cascade utilization system in which the first stage is electricity generation, followed by district heating, agricultural utilization, heating and water supply for thermal baths, and finally heat-pump utilization before reinjection.

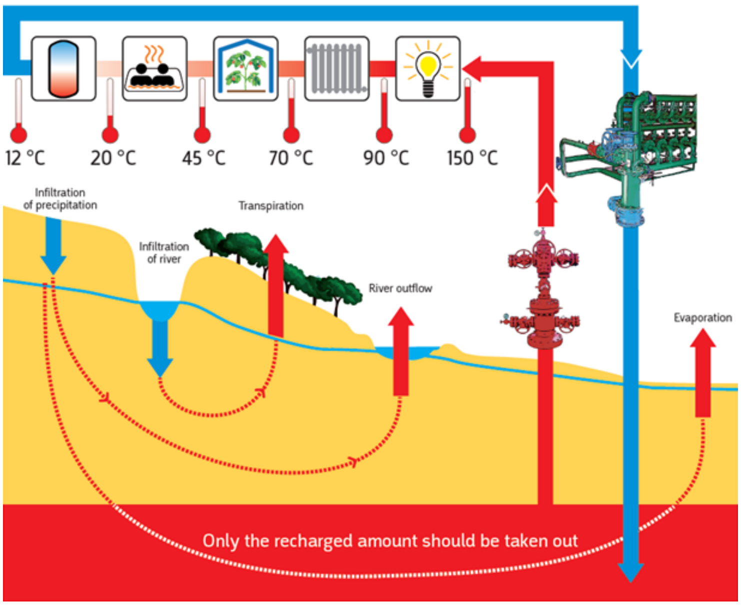


Figure 33 - The scheme of an optimal geothermal cascade system to utilize the biggest heat amount.(modified after Szanyi et al., 2015)

Geothermal district heating systems are becoming more common, such as the Hódmezővásárhely (Hungary) cascade system of 18 MW(th) capacity, operating since 1994; the 24 MW(th) Oradea (Romania) geothermal system currently under development; and the establishment of two major geothermal district heating projects in Hungary such as Miskolc of 55 MW(th) and Győr of 52 MW(th) that target basement carbonate reservoirs.

Currently, the largest investments are related to development of the district heating system of Szeged, Hungary (population ~200,000). During the project, 27 new wells (9 production and 18 injection) are being drilled in the city to approximately 2,000 m depth. Each production well is expected to yield over 1,000 m^3/day of 90 °C-water. The integration of geothermal energy is expected to cut the total gas consumption of the district heating system by ≈50 percent.

A major step in deep geothermal exploration and exploitation in the Pannonian Basin was the first geothermal power plant commissioned in 2018 in Tura, Hungary, with electrical power generation capacity of 2.3 MW(e). The largest binary technology geothermal power plant in continental Europe started operating in 2019 near Belovar, Croatia, with an installed capacity of 17.5 MW(e). Further ongoing geothermal power projects are taking place in southern Hungary and the Dráva Basin of Croatia. Romania and Serbia are also planning to build geothermal power plants.

Geothermal well data for Hungary can be downloaded for free from the digital database OGRe – National Geothermal System↗.

7 Petroleum Hydrogeology

Petroleum hydrogeology is a new integrated exploration tool used to find hydraulically trapped hydrocarbons. This is a subdiscipline of hydrogeology introduced in 1978 (Tóth, 1978: Red Earth study), which has been successfully applied thus far in the Rhine Graben, the Pannonian Basin, and the Western Canada Sedimentary Basin.

Early exploratory drilling conducted between 1920 and 1960 discovered small gas accumulations and some condensate in the Great Hungarian Plain that were commercially disappointing at first and ended up providing deep artesian wells that produce warm to hot groundwater (Dolton, 2006; Royden and Horváth, 1988). The first significant oil and gas accumulation of real commercial value was discovered at Algyő in 1965 by the National Oil and Gas Trust (OKGT). This field is approximately 250 km^2 and is located near the city of Szeged, Hungary, by the southern reaches of the Tisza River, in the area of lowest ground elevation in the basin of about 80 masl. Subsequent drilling at the Algyő field during the 1960s to 1980s uncovered several stacked pools of gas, condensate, and some oil at depths ranging from 2,000 to 3,700 m below ground in clastic deposits consisting of sandstone, siltstone, marl, and turbidite. Such an encouraging discovery led to broader petroleum exploration in other parts of the Pannonian Basin—not just on the Hungarian side of the basin but also in Romania and former Yugoslavia, today's Serbia and Croatia. Several economically viable petroleum fields were discovered over the past 60 years, and some are still producing. Figure 34 shows the distribution of producing fields in the Pannonian Basin.

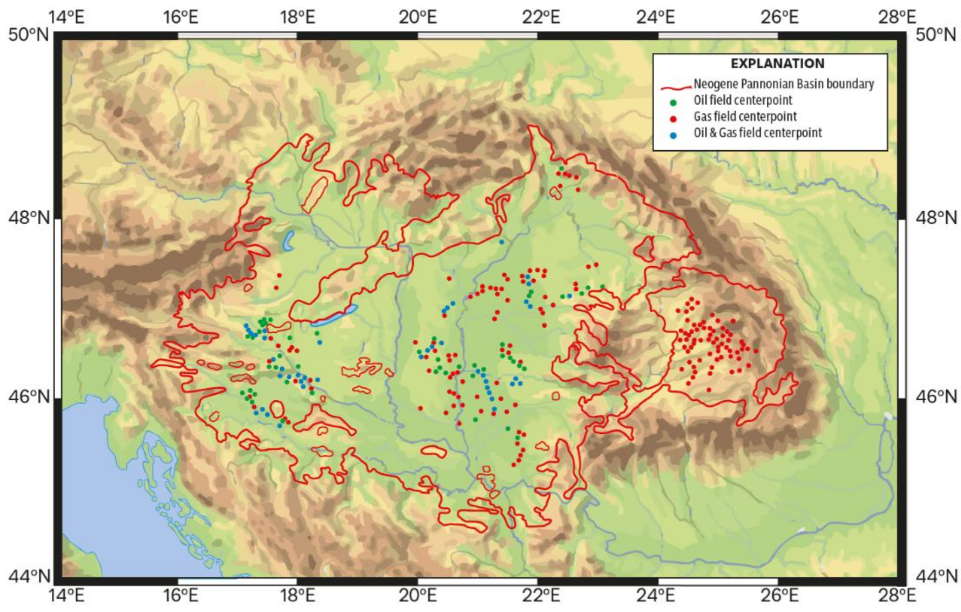


Figure 34 - The location of Hydrocarbon pools in the Pannonian Basin (based on Dolton, 2006).

Initial exploration efforts were hindered by the discovery of unusually high temperatures (often above 200 °C) and fluid pressures as high as 5 to 25 MPa above normal hydrostatic that were encountered at depths exceeding 2,500 m. Several drilling attempts were marred by catastrophic well blow-out incidents, where the entire drilling rig set-up was destroyed and personnel were seriously injured. Advanced drilling techniques and well control technologies were required for safe and successful discovery, development, and production of these hydrocarbon accumulations.

Throughout the Pannonian Basin system, gas reservoirs commonly contain substantial quantities of CO_2 because of high geothermal gradients and carbonate decomposition in deeply buried basement rocks. Values of CO_2 content range from 0.5 to 99.5 percent and average 28 percent.

More than 4,000 producing pools are found in the Pannonian Basin, with depths ranging from 80 to about 5,000 m. Most oil pools were found in the 800 and 3,000 m depth range. Gas pools are found across a larger depth range, extending to 6,000 m depth. Most gas pools found below 3,000 m depth are associated with shale gas accumulations within the Endrőd Formation (Figure 14). A wide variety of structural, stratigraphic, and hydraulic trap types and a combination thereof is present. Common structural traps include compactional anticlines over basement highs (i.e., stratigraphic traps), fault-closed features, roll-overs associated with growth faults, closures in flower structures along strike-slip faults, and inversion structures generated by shear and compression (Figure 35).

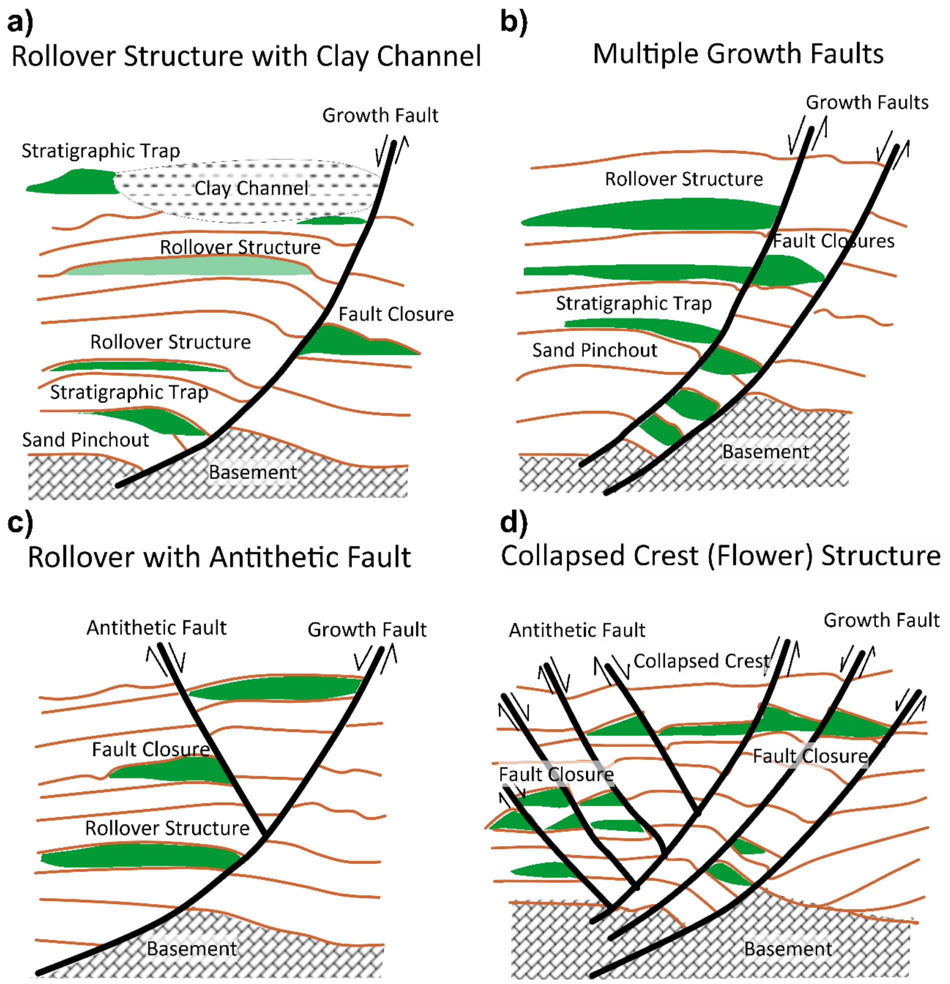


Figure 35 - Trap types in structurally deformed deltaic deposits (modified after Fagbemigun et al., 2021).

Stratigraphic traps include pinch-outs in fluvial, shallow water, and turbidite sandstones and conglomerates; in patch reefs; and at truncations—particularly at the unconformity between syn-rift and post-rift rocks. The traps are sealed by fine-grained sediments such as shale, clay-marl, and marl, which have very low permeability and thus restrict further movement of hydrocarbons.

The early hydrocarbon pool discoveries turned out to be associated with basement highs (also known as *horst*), or sedimentary structures developed above such basement features. Exploration of sub-basins formed in basement depressions (also known as *grabens*) was initially hindered by thermal and overpressure challenges encountered during drilling. However, modern drilling techniques allow for adequate pressure control and logging of deep sediments.

Several oil and gas accumulations were discovered in such sub-basins, and the location of deep source rocks was ascertained. Early paradigms suggested that oil and gas pools would preferentially accumulate in anticlinal structures, by *up-dip* migration of petroleum, driven mainly by buoyancy forces enhanced by vertical compaction. These paradigms were based on geological and structural mapping of petroleum fields. Regional basin scale-mapping of geology, structures, petroleum accumulations, and fluid-potential distribution allowed for recognition of alternative petroleum migration, possible remigration, and entrapment (Almási, 2001).

Within the gravity-driven flow regime of the Pannonian Basin, hydrocarbons tend to accumulate in hydraulic traps associated with discharge areas and stagnation zones of convergent or divergent flow systems of a different order (i.e., local, intermediate, and regional flow systems).

In the deep over-pressured regime, hydraulic trap configurations were identified on fluid-potential maps and cross sections (Almási, 2001). The fluid potential maps were prepared for distinct elevation intervals akin to tomographic slices, where fluid pressures of groundwater and hydrocarbons measured within each elevation interval (tomographic slice) were plotted as "freshwater equivalent hydraulic heads". The fluid-potential anomalies tend to coincide spatially with lithological and structural contrasts that can be observed on geologic maps and vertical cross sections. Given that not all such geologic features create fluid traps, the addition of fluid-potential tomographic maps improves identification of prime exploratory drilling sites. The magnitude of local hydraulic gradients and their distribution pattern can indicate permeability distributions that control the rate of petroleum migration or lack thereof. On horizontal fluid-potential maps prepared for depth ranges below -2,000 m asl within the overpressured regime, hydrocarbons are commonly found in traps associated with fluid-potential highs (mounds and ridges) or along escarpments (Figure 36). Within the deeper overpressured groundwater flow regime, oil and gas pools are sometimes associated with the fluid-potential configurations depicted in both Figure 36 and Figure 37.

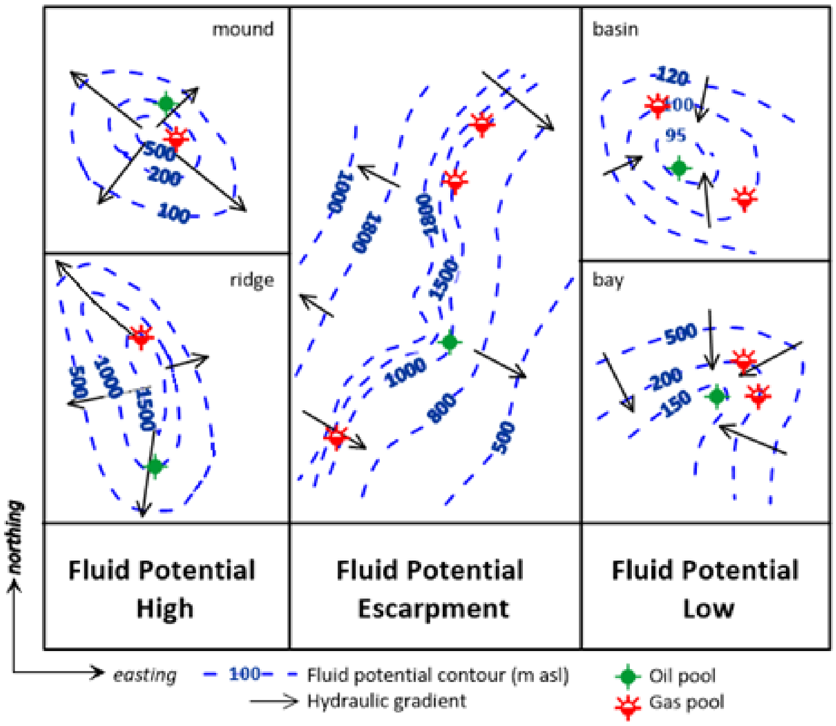


Figure 36 - Schematic illustration and classification of diagnostic fluid potential map anomalies identified in tomographic slices of various elevation intervals (after Tóth and Almási, 1998).

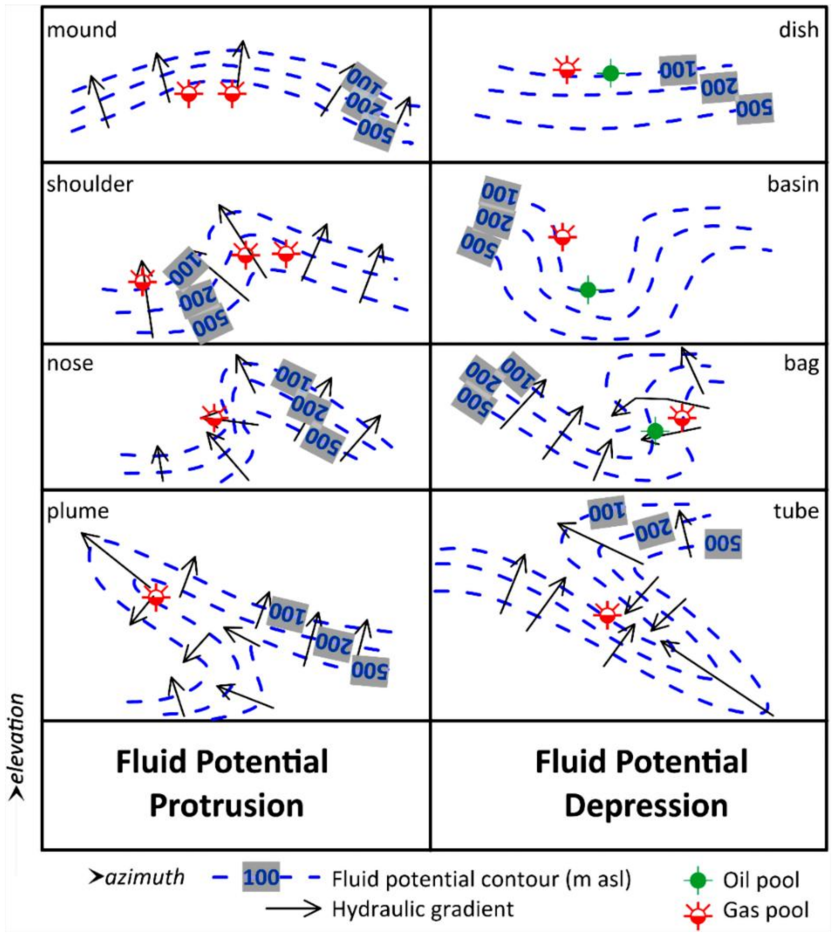


Figure 37 - Schematic illustration and classification of diagnostic fluid potential anomalies identified on hydraulic cross-sections (after Tóth and Almási, 1998).

Based on spatial analysis of petroleum accumulations and fluid potential anomalies characteristic of trapping conditions in the Great Hungarian Plain, Almási (2001) concluded the following.

1. Several petroleum accumulations in the basin can be linked to the present-day groundwater flow-field.
2. Gravity-driven groundwater flow seems to enhance the potential for trapping hydrocarbons within the quasi-hydrostatic zone under both recharge and discharge areas.
3. The position of most petroleum accumulations discovered within the overpressured zone can be explained with compactional groundwater flow models.
4. Several accumulations of hydrocarbons within the overpressured zone in regions of dominantly ascending flow can be linked to either earlier compactional flow directions or present-day flow directions.
5. Hydrocarbons could have been (or may be) redistributed from above basement highs toward graben centers along the lateral component of regional groundwater hydraulic gradients.
6. Internal parts of the grabens are promising areas for hydrocarbon exploration.

8 Wrap-Up

The Pannonian Basin in central-eastern Europe is one of the world's most complex hydrogeological systems where gravity-driven flow regimes are stacked on tectonically overpressured fluid regimes. Flowing artesian conditions are widespread across the basin and are manifested in many ways from both clastic deposits and karstic systems. Geothermal anomalies stemming from the structural architecture of the basin system are exhibited on the surface by the high density of thermal wells producing groundwater with temperatures exceeding 30 °C—as hot as 100 °C—and steam. Exercise 4↴ provides an opportunity for readers to recall the characteristics of the Pannonian Basin that are presented in this book.

As a landlocked intermontane basin, groundwater is the primary source of drinking water for the population of nine countries sharing the resources of the basin. Therefore, sustainable use of groundwater and implementation of pragmatic water management practices are responsibilities shared by all inhabitants and regulatory agencies of countries occupying parts of the basin.

Hydrocarbon resources in the Pannonian Basin system are modest relative to other basins in the world. However, groundwater flow system analysis in conjunction with traditional geological and geophysical exploration methods known as *petroleum hydrogeological exploration* has been proven as a successful unifying method by which to explore this basin, and is applicable to other geological basins around the world.

9 Exercises

Exercise 1

Which answer is true? In the case of a gravity flow system:

1) the highest dissolved salinity is expected in the local recharge area.

2) the highest dissolved salinity is expected in the regional discharge area.

3) groundwater age and dissolved salinity are correlated.

Solution to Exercise 1⤵

Return to where text linked to Exercise 1⤵

Exercise 2

a) Design a gravity driven flow system of your choosing using TopoDrive↗. This 15-minute video describing the use of TopoDrive↗ may help you get started. Explain why you chose the features and properties.

b) Before running the model, describe what you envision the equipotential lines and flow lines will look like, where you think the particles will go, and how long it will take a drop of water to move from the recharge to the discharge area.

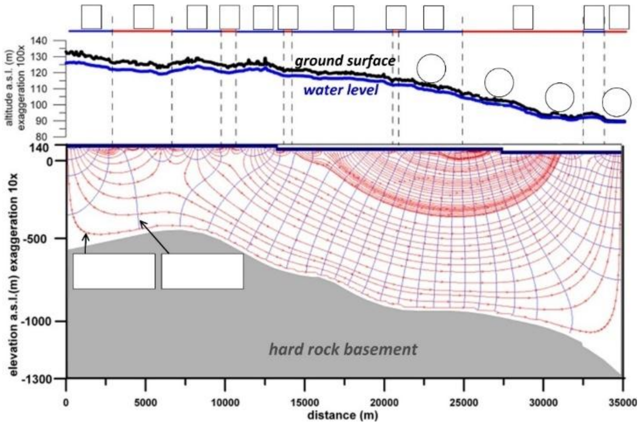
c) Run the model and explain how the results differed from your expectations and why. Include a snapped image of your flow lines and particle paths.

Solution to Exercise 2⤵

Return to where text linked to Exercise 2⤵

Exercise 3

Indicate in the squares which area belongs to the recharge (R) and which to the discharge (D) zone. Write the letter of the photo of the plant communities shown in Figure 20 into the appropriate circle, and in the rectangles indicate which is the flow line and which is the equipotential line.



Exercise 3⤵

Return to where text linked to Exercise 3⤵

Exercise 4

What are the main features of the hydrogeology of the Pannonian Basin?

1) Climate
2) Physiography (topography and drainage; surrounding mountains, major rivers)
3) Geology:
    a. Structural type of basin
    b. Minimum crustal thickness
    c. Age and maximum thickness of basin fill
    d. Main depositional facies
4) Hydrostratigraphy:
    a. regionally unconfined aquifers
    b. regionally confined aquifers
5) Types of Flow Regimes
6) Geothermal Conditions:
    a. Geothermal gradient
    b. The anticipated water temperature from a 2,500 m deep well
    c. Principal geothermal reservoirs
    d. Types of geothermal energy utilization
7) The most common hydraulic traps for mineral and petroleum accumulation.

Solution to Exercise 4↴

Return to where text linked to Exercise 4↴

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11 Exercise Solutions

Solution Exercise 1

Statements 2 and 3 are true:

2. The highest salinity is in the regional discharge area.

3. Groundwater age and dissolved salinity are correlated.

Return to Exercise 1⮥

Return to where text linked to Exercise 1⮥

Solution Exercise 2

All responses will differ even the same person will not be able to create exactly the same model twice because of the free hand drawing involved in the creation. If you are studying with others, it would be useful to discuss your explorations and conduct further models in response to your findings.

a) I designed 2 systems. Both were only 1000 meters wide and drawn with no vertical exaggeration. The default values of hydraulic conductivity and isotropy were not altered from the default values for each color.

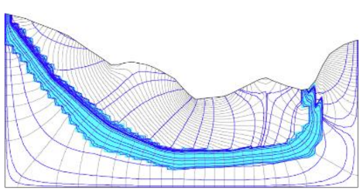
   1. System 1 has rugged terrain and a high hydraulic conductivity unit extending from a ridge below the lowest point and outcropping on the other side. I was wondering if it would carry water below the lowest drainage to the other side of the basin.
   2. System 2 is homogeneous. I wanted to see the hierarchy of flow systems. The shape of the water table and the hydraulic conductivity distributions are shown in the first snapped image of part (c).

b) My expectations:

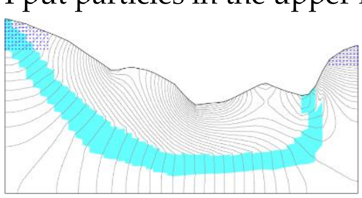
   1. For the first system I expected most of the flow lines and particle paths to follow the high conductivity unit. I expected groundwater to flow rapidly in the high hydraulic conductivity unit and slowly in the rest of the system.
   2. For the second system I expected to see the hierarchy of flow systems as shown on the right side of Figure 17. I expected shallow groundwater to flow quickly from recharge to discharge areas and deep groundwater to take much longer.

c) Results varied from my expectations:

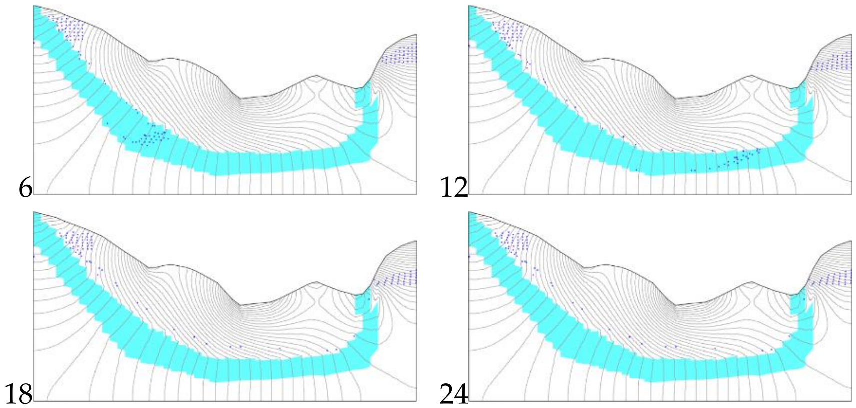
   1. The first result flow lines were as expected:



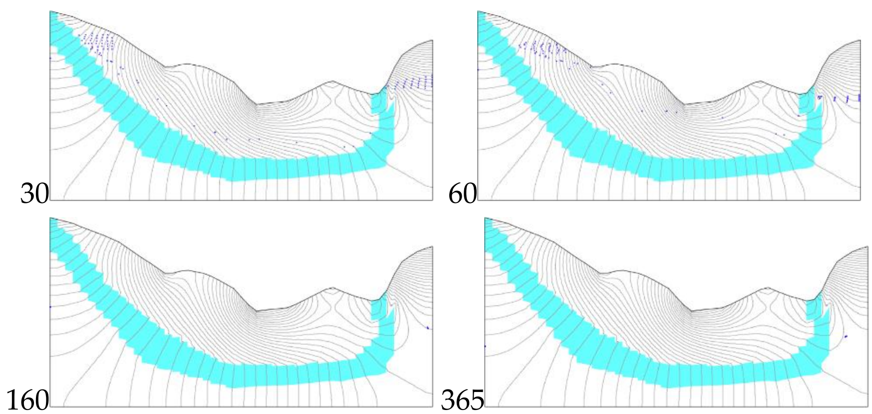
I put particles in the upper left and right corners



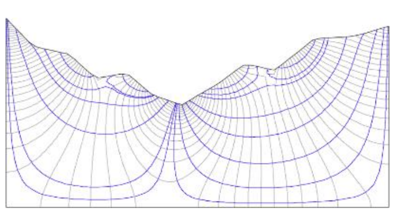
I did not expect particles to move as fast as they did because I know groundwater moves slowly. This is their location after 6, 12, 18 and 24 days. In only 24 days the particles in the high hydraulic conductivity unit had exited the system. I realized that given my short basin and steep slope, the gradient was high and with the high hydraulic conductivity, the velocity was high.



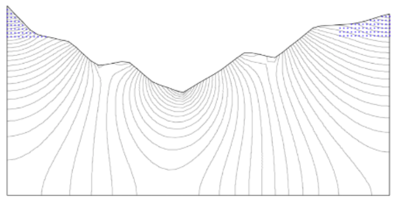
After 30, 60, and 120 days the particles in the low hydraulic conductivity unit have nearly exited the system. By 365 days there are a few particles left that stagnated on the left and right, and all have exited the system by 580 days. Again, this rapid movement was not expected. In the future I will specify a longer basin and include vertical exaggeration so I can see the details in the vertical direction.



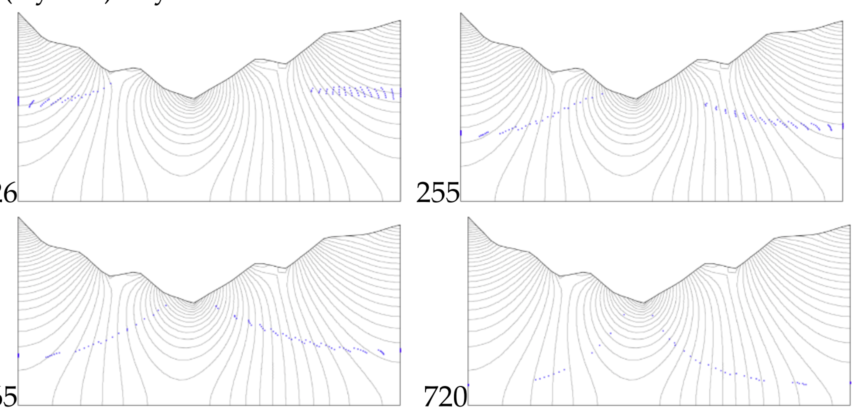
2. The second results were also somewhat unexpected. I thought the local, intermediate, and regional flow systems would be more distinct. I conclude this is due to the short width and significantly large death of the system. It will be interesting to explore different depth/width ratios in future models.



I put particles in the upper left and right corners.



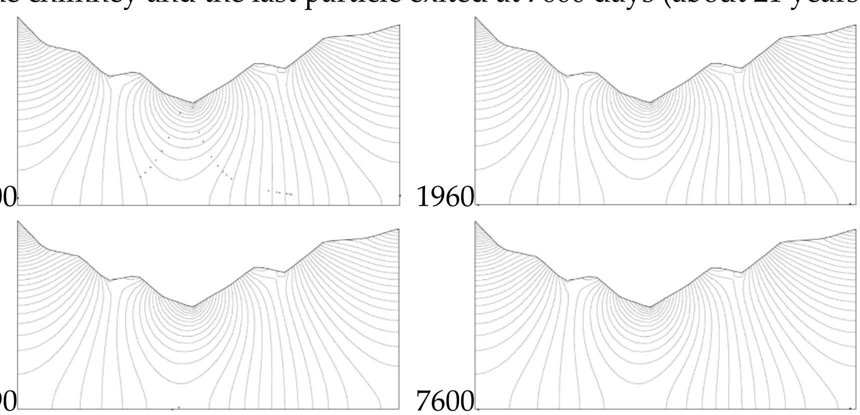
The particles moved slower given the lower hydraulic conductivity. This is their location after 126, 255 (when the first particle exited), 365 (a year), and 720 (2 years) days.



126 255

365 720

Not long after 1100 days nearly all particles had exited the system. By 1960 days a few particles were in the stagnation zones in the lower left and right corners. By 4690 days they were at the bottom center of the basin ready to move up the chimney and the last particle exited at 7600 days (about 21 years).



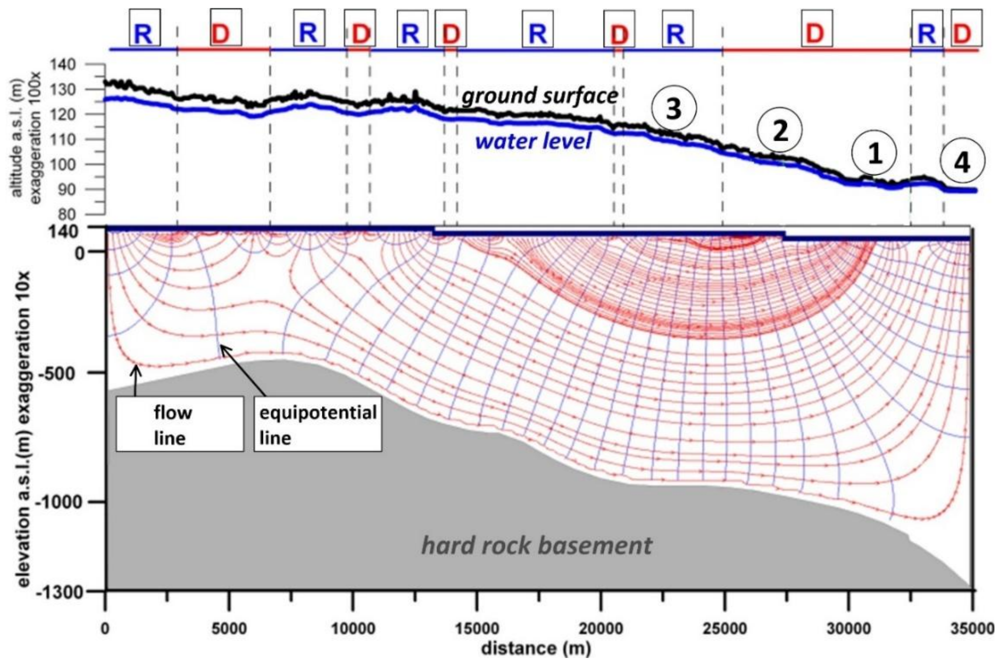
1100 1960

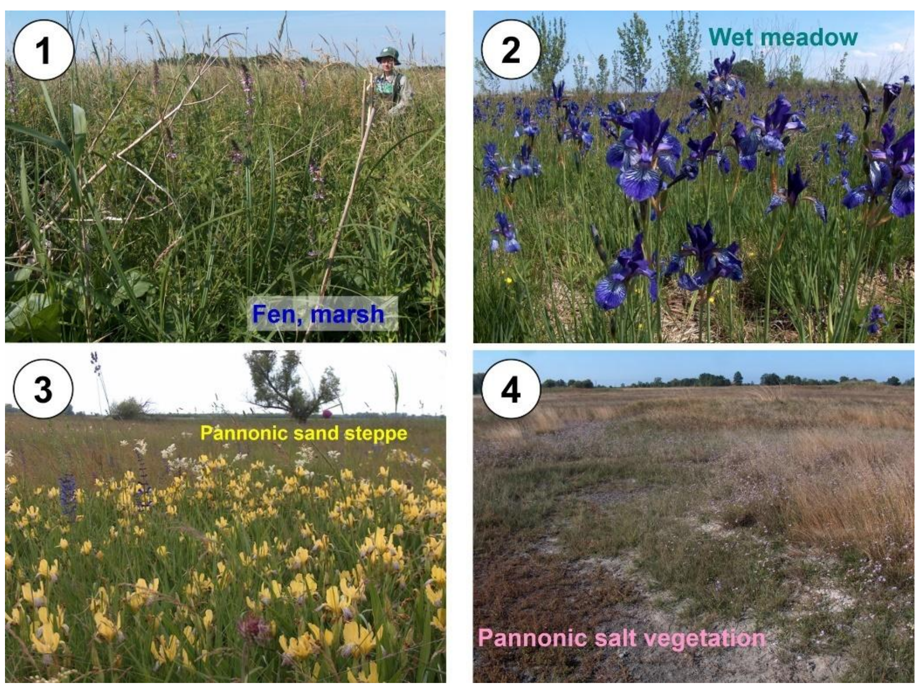
4690 7600

Return to Exercise 2↥

Return to where text linked to Exercise 2↥

Solution Exercise 3





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Solution Exercise 4

1) Climate: Continental-temperate with mean annual air temperature between 9.3 and 10.8 °C; the average annual precipitation ranges from 490 to 627 mm/yr (~ 80 percent is in the form of rain); the actual evapotranspiration ranges from 513 to 622 mm/yr, while the potential evapotranspiration ranges from 750 to 900 mm/yr.
2) Physiography (topography and drainage): Intramontane basin, surrounded by the Carpathian Mountains to the north and east, by the Southern Carpathians and Dinaric Mountains to the south, and the Southern and Eastern Alps to the west. The plains within the Pannonian Basin are flat, with a regional relief of about 0.1 to 3 m/km and a mean elevation of ≈110 masl. Approximately 68 percent of the area of the Pannonian Basin is lowland with elevations below 200 masl. The Pannonian Basin is an integral part of the larger scale Danube River Basin. The basin is drained along the middle by the Danube. Large tributaries of the Danube within the basin system include the Sava, Dráva, and Tisza rivers.
3) Geology:
   a. Structural type of basin: back arc basin.
   b. Minimum crustal thickness: ~26 km.
   c. Age and maximum thickness of basin fill: started approximately 17 million years ago during the late/middle Miocene. Maximum thickness exceeds 7 km in deepest sub-basins.
   d. Main depositional facies: seven depositional units from bottom to top are
      - basal unit
      - deep basin unit
      - prodelta turbidite unit
      - delta slope unit
      - delta front-delta plain unit
      - alluvial plain unit
      - terrestrial unit.
4) Hydrostratigraphy:
   a. regionally unconfined aquifers: Nagyalföld Aquifer.
   b. regionally confined aquifers: Szolnok and Pre-Pannonian aquifers.
5) Types of Flow Regimes: gravity-driven flow regime underlain by an overpressured flow regime.
6) Geothermal Conditions:
   a. Geothermal gradient: range is 50 to 60 °C/km.
   b. The anticipated water temperature from a 2500 m deep well: 130 to 140 °C.
   c. Principal geothermal reservoirs: karst and clastic deposits.

d. Types of geothermal energy utilization: spa, agriculture, district heating, industrial space heating, and electricity generation.

7) The most common hydraulic traps for mineral and petroleum accumulation: Stagnation zones of convergent and divergent flow systems of various hierarchical orders, and discharge areas.

Return to Exercise 4⮥

Return to where text linked to Exercise 4⮥

12 About the Authors

István Almási earned his Master of Sciences in Geology from the Eötvös Loránd University, Budapest, Hungary, and his Doctor of Philosophy degree in Earth and Atmospheric Sciences (specialization in Petroleum Hydrogeology) from the University of Alberta, Edmonton, Canada. He specialized in basin scale petroleum exploration using hydrogeological, structural geological, and geothermal methods in the Great Hungarian Plain, Pannonian Basin.

Subsequently, he worked as consulting hydrogeologist and as development geologist for Shell Canada Limited. Since 2011, he operates Dome GeoConsulting Inc., providing services in applied hydrogeology for mining, oil industry, water supply, civil infrastructure design and construction, and environmental hydrogeology. He participates in karst hydrogeology research and exploration projects in Alberta, Canada. In 2018, he was co-recipient of the Canadian Society of Petroleum Geologists' Medal of Merit Award for his work on the hypogenic karst beneath the Athabasca Oil Sands.

János Szanyi earned his Master of Science degree in Mathematical and Computer Science, and Geology and Doctor of Philosophy degree in Environmental Sciences at the József Attila University, Faculty of Natural Sciences, Szeged, Hungary. Subsequently, he specialized as a Hydrogeological Engineer at the Miskolc University, Hungary.

He worked for the Hungarian Geological Survey for 12 years, starting off as a field geologist and later became the head of the regional office in Szeged. His career focused on applied hydrogeological and geothermal projects including planning and executing field work and compiling geothermal databases. He also coordinated several international geothermal projects that dealt with transboundary aquifers and participated as a modeling expert and project manager for several geothermal energy utilization projects. He teaches hydrogeology, modeling groundwater and heat flow, and geothermics at the University of Szeged, Hungary. He is the coordinator of the Panel of Experts on Geothermal Energy at the European Federation of Geologists.

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