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GeoCom – FP7 CONCERTO – 239515

TRANSBOUNDARY UTILISATION MODEL

D5.2 – Final version

WP Leader: P9 – University of Szeged.
Key Contributors: P1, P14
2012

GeoCom

The water base model of the Szeged – Morahalom – Subotica triangle

WP5.2. Transboundary issues of the utilization of geothermal energy

University of Szeged
2012.

WP5.2 Transboundary issues of the utilization of geothermal energy The most significant thermal water resource in the Carpathian Basin can be found under the territory of the Hungarian-Serbian border, in the Szeged-Morahalom-Subotica triangle. The abstraction for extensive and complex utilization is currently being started on both sides of the border. For the safe and sustainable abstraction, and its international monitoring, it is necessary to determine the hydrogeological-hydrodynamic features of the common thermal water base, and to elaborate a two-phase 4D model of the water base for the mapping of the water resource and its gas content.

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THE WATER BASE MODEL OF THE SZEGED – MORAHALOM – SUBOTICA TRIANGLE FOR THE ASSESSMENT OF THE IMPACTS OF THERMAL WATER PRODUCTION FROM PANNONIAN LAYERS OF THE THERMAL WATER RESERVOIRS IN THE HUNGARIAN-SERBIAN BORDER REGION

The objective of the study is the familiarization with the Pannonian formations of the main reservoir of the examined area and the assessment of environmental impacts of thermal water production with special regard to the pressure changes in certain isolated Upper Pannonian aquifers in the Szeged-Mórahalom-Subotica triangle. Within the research, a uniform geological picture of the border region was created that served as a basis for model calculations. The model calculations were run according to the possible future scenarios (4D).

The data of the different water withdrawal objects in the related area (water production wells, thermal wells) and the sections of the area's geological structure were provided on the Hungarian side by the *Water Management Directorate of the Lower Tisza Region (ATIVIZIG)* and the *Geological Institute of Hungary.* The data of the Serbian side were provided by a geothermal thesis research written at the *University of Szeged.*

The analysis shows the cross-section of the water withdrawals in the related water reservoirs by the current industrial and domestic water consumption. Scenarios were created on the current and possible future water withdrawals affecting the water supply in cases when the extracted water quantities increase by 25% and 50%.

Geological environment

Geological evolution, geothermal features, thermal water supply

The analyzed territory is part of the Great Plain, which is a sedimentary Neogene basin with thick water-bearing layers. The crystalline bedrock comprises mountain ranges with great level differences and deep trenches that were covered by the sediments of Tertiary seas and lakes and Quaternary rivers. The thickness of the sediments above the crystalline ridges is of 1,000-2,000 metres, and of 5,000-6,000 metres above the deep trenches. The Mesozoic carbonate and Palaeozoic metamorphic rocks of the bedrock rise to heights of several thousands of metres above the surface in the marginal regions of the Great Plain.

The depressions of the Carpathian basin were covered by Parathetys seas in the eras prior the Pannonian, from the basin of today's Mediterranean Sea to the Indian Ocean. These Parathetys basins lost their connection only during short regression periods. Even if Neogene layers were formed before the Pannonian era in the South-Eastern Great Plain, the majority of these were eroded in the elevation period in the Sarmatian era. The sea in the Pannonian Basin lost its connection to the World Ocean 12 million years ago, at the end of the Sarmatian era due to the mentioned elevation and a possible eustatic rise of the sea level (Vakarcs et al., 1998). Starting from this period, we speak about a Pannonian era that contains the evolution of the Pannonian Sea that lasted according to Hungarian literature from the end of the Sarmatian Epoch to the full filling in the Pleistocene Epoch. At the beginning of the Pannonian era, the Carpathians and

Alps, Dinarides emerged to significant heights, while the Great Plain behind them started an intensive sinking. This sinking was caused by the fact that the crust under the Pannonian Basin became thinner, allowing favourable geothermal features. The Great Plain comprised unequally sinking basins throughout the epoch, and these were filled with a large quantity of sediment from the affluent rivers flowing from the bordering regions. The majority of Hungary's thermal water can be found in the sediments formed during these 8-10 million years. The sediments deposited until the sweetening of the sea are classified under the Lower Pannonian stage of the Pannonian era, characterized mainly by marine (and towards the end by bog) marls and hard sandstone. The thermal water in the Lower Pannonian layers are of high temperature and slightly saline. The half lentic-half fluvial Upper Pannonian formations with an average thickness of more than 900 metres contain a more significant quantity of thermal water. The majority of the thermal wells in the model area are filtered in a depth of 10-20 metres in the sandstone layers of these formations. The Pannonian formations are presented in detail in the next chapter (Kőrössy, 1984).

The filling-up of the basin happened in the basin parts with significant time differences. The Gilbert deltas started to deposit their terrigenous sediments at the very beginning of the Pannonian era from NW and NE directions and reached the basins in the South Great Plain much later, where thick pelagic layers were formed. The sediments from the filling-up directions merged in the Békés Depression, since this was the last region to be filled up (Juhász, 1992). The sediments of the NW delta system can be traced in the model area.

The tectonic processes of the Pleistocene period significantly transformed the situation of deposited sediments. Some areas, such as the depression near Szeged, sank 600-700 metres, while the Danube-Tisza Interfluvial region only 100-200 metres. The level difference of adjacent sediments of level lands reached several hundred metres; accordingly, the Quaternary layers are of different thickness. The sediments of the Pleistocene period are the best aquifers; however, since they are shallow, only an insignificant part of these can be found below the isotherm of 30° C, thus they are not very rich in thermal water (Kőrössy, 1984).

The thin crust under the Pannonian Basin explains the favourable geothermal features of the area. Accordingly, the heat flux on the surface is around 90 MW/m^2, which is 50% higher than the European average. In Europe, in areas beyond the Carpathians, the geothermal gradient is of 30-33 m/°C, while the average temperature gradient of the deep waters of the Great Plain is of 18 m/°C (Kőrössy, 1984).

In Hungary, the subsurface waters with an outflow temperature above 30 °C are called thermal waters. From the porous layers of the model area we can produce hot water with a temperature to 80-100 °C. The geometry of the layers of the model area is shown on **figure 2.**

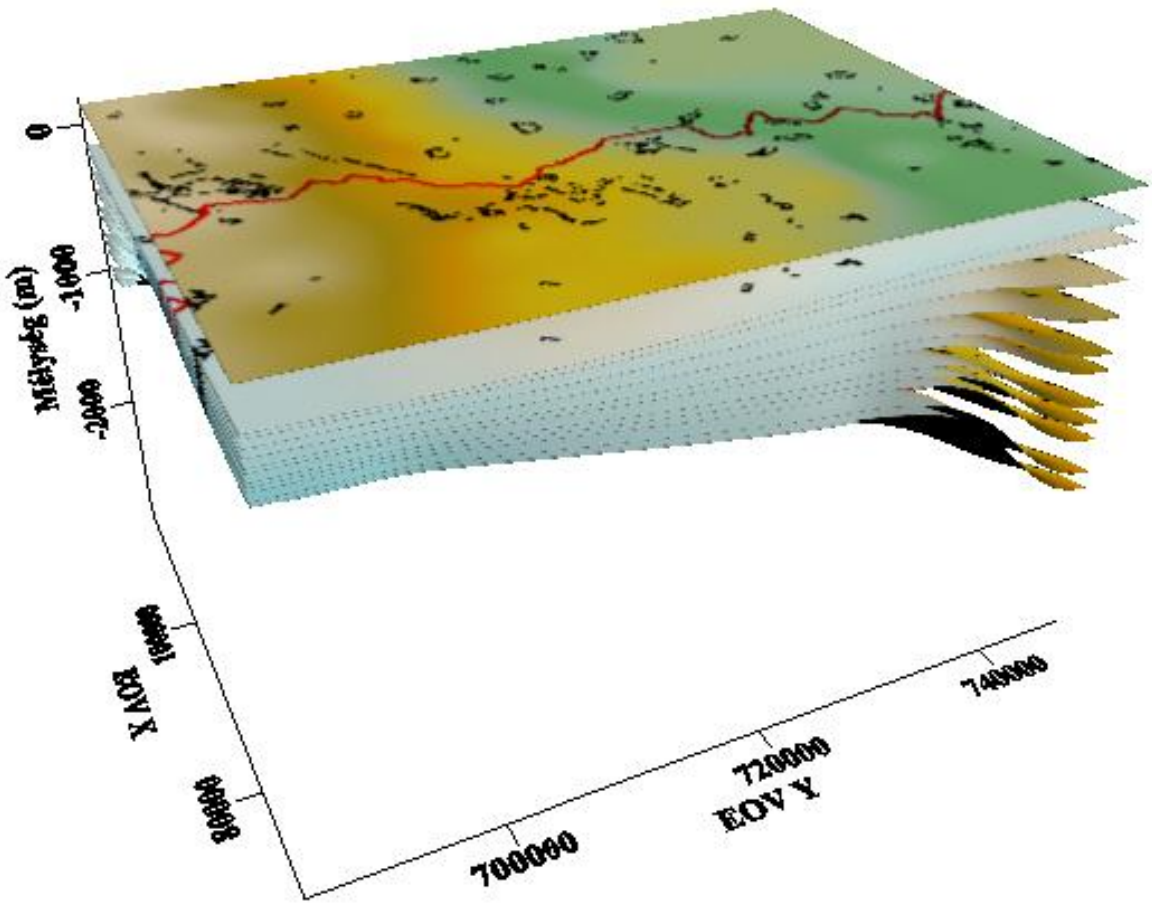

Fig. 2: Geometry of layers under the model area. (Source: Kárász, 2010)

Presentation of the porous Neogene formations in the SE part of the Great Plain, with special regard to the thermal water-bearing Pannonian layers.

The Pannonian formation of the South Great Plain is described according to Györgyi Juhász.

Békés Formation: It is not of an average spreading, it is connected to the Algyő Ridge in the Makó-Hódmezővásárhely depression. The Pre-Pannonian stratum can be found in its substratum, the Tótkomlós Section of the calcareous marly Endrőd Formation in its superstratum. The Békés Formation is a riparian detrital formation. It formed around the earlier isles in the inner part of the basin. Its rocks contain oligomict fine-grained conglomerate and gravelly large-grained sandstone from the surrounding bedrock. Its average thickness reaches 30-40 metres.

Endrőd Formation: Its substratum is mainly Pre-Pannonian stratum, the sediments of the Békés Formation can be found above the bedrock. The deep turbidite system of the Szolnok Formation is its upper boundary; where this is missing, it goes over into the lithologically similar Algyő Formation. This pelitic, "basal marl" formation formed in diverse water depth conditions is quite spread in the Great Plain. Its thickness can

reach from 100 metres to 700 metres. The layers start with marl, calcareous marl (Tótkomlós Section), and changes to hemipelagic clay marl (Nagykörü Section) The marl (Dorozsma Section) contains lines of gravels from the bedrock in areas with abrupt base morphology. More and more aleurolite-sandstone lines can be found towards the top of the formation (Vásárhely Section), gradually introducing the turbidite sedimentary body of the Szolnok Formation.

Szolnok Formation: Its lower boundary is the Endrőd Formation, its upper the Algyő Formation. This formation is mainly present in the deeper zones of the basin, reaching a thickness of approx. 1,000 metres, and excellently following the base morphology. It is a deep turbidite system with fine-grained sandstone and clay marl, almost every element of the gravitational forming of sediments can be found in it. The pelitic formations are dominant at the bottom, the number of sand layers and their thickness grows towards the upper layers. The very thick turbidite sets are more common in the W part of the Great Plain. This body of sediments was most probably deposited by a delta prograding from NW direction, transporting very sandy sediments, and with many parallel beds that were frequently changed. This formation contains the layers with the most favourable water-bearing features among the Lower Pannonian formations.

Algyő Formation: Its lower boundary is the Szolnok Formation, where that on is missing, it formed gradually from the Endrőd Formation. Its upper boundary is the Újfalu Formation, which marks the beginning of the Upper Pannonian formation. This borderline is a diachronic facies border that becomes constantly younger from the main filling-up directions towards the Békés-Basin that was filled up last. The Algyő Formation is mainly pelitic, with clay marl and aleurolite layers, and occasionally sandstone bodies between them. Its thickness reaches 200-1000 metres. It represents delta and basin bank facies, and inland sea sedimentary facies at the boundaries far from carrying directions. The sandstone bodies in the formation were formed through sliding and flowage at the bottom, higher they are turbidite bed deposits, and at the top bar deposits.

Újfalu Formation: Its lower boundary that separates it from the Algyő Formation is the traditional boundary between the Lower and Upper Pannonian layers. The Zagyva Formation can be found in the superstratum around the depressions of the basin, while sandy bed filling facies were formed in the Danube-Tisza Interfluvial region and close to the other carrying boundaries, thus in these areas it is overlain by quaternary layers. Its average thickness reaches 300-400 m. The Újfalu Formation contains mainly fine and medium-grained sandstone layers, with clay marl and aleurolite layers between these. Riparian shallow-water sediments constitute 70-80 % of the layers. The majority of the sediments were formed in the deltafront and the delta flats. The small proportion of thin aleurolite and clay marl layers indicate a fast sediment accumulation, and a sediment transport of a high-energy medium. Pelitic layers are usually thinner than five metres between the sand layers, fact that implies an excellent water-yielding capacity. The sand layers can be originated from bar deposits, delta bed filling, redepositions and dam breaking, while the pelites are marsh, floodplain and dead-channel facies that show the filled status of the Pannonian Sea during the Upper Pannonian era. The progradation of the delta system is indicated by the fact that it evolves from pelitic sediments of the delta bank with coarse-grained bar deposits; where the delta distributaries cut in the layers below them, the formation begins with bed filling.

Zagyva Formation: Its base is always the Újfalu Formation. Its superstratum is the Nagyalföld Formation; in places where this disappeared, it is covered by quaternary layers. Its spreading is not general, it is located in areas where the Great Plain showed the most intensive sinking during the era. It pinches out in the Danube-Tisza Interfluvial region. The formation is characterized by monotonous variation of thin and dense layers of clay, aleurite and sandstone, dominated by pelitic sediments, thus it is a weaker aquifer than the Újfalu Formation. The set layers deposited in alluvial plains, floodplains, riverbeds, marshes and dead channels in the final stage of the Pannonian Sea. The 5-20-m sandstone layers represent mainly facies of bed fillings, floodplain sediments or dam breaking.

Nagyalföld Formation: According to the available data, it is not separated in any form from the Zagyva Formation below it. Just like the layer below it, this formation contains alluvial plain facies, the only difference being the frequent multicolour clay and paleosoil layers, fact that results in a water-yielding capacity worse than the on of the Zagyva Formation.

The Quaternary starts with the drying out of the Pannonian Sea, with the deposition of fluvial and Aeolian sediments. The Pannonian-Pleistocene change of sediments was a quite long process. The marshy areas that remained on the place of the Pannonian Sea dried out and then filled up, washing away the developing soil formations. This process took place at the limit of the Upper Pannonian and Quaternary eras. The formation of the temporary Levanian layers of mixed and multicolour clay began at the end of the Pannonian era (Nagyalföld Formation) and ended in the Quaternary. This is a layer with bad water-yielding capacity; they are reservoirs of several tens of metres that can be linked to the direct environment of the former riverbeds, delta banks, delta fronts and delta plains.

The Quaternary rivers deposited layers rich in sandstone and with good water-yielding capacity during the 2 million years. The thickness of the Pleistocene layers in the western part of the SE Great Plain, in the Danube-Tisza Interfluvial region is of 200-300 metres, in the region of Szeged, it reaches 400-600 metres (Kőrössy, 1984).

Hydrogeological, hydrodynamic features of the Southeast Great Plain

The Great Plain is a basin filled with of loose sediments, separated into several different parts, but in its entirety, it is a big water reservoir. The water flows horizontally and vertically between water-barring (leaking) and water permeable layers at different speed rates from places with higher potential towards the ones with smaller potential. The connection of the reservoirs is caused by the fact that the continuity of impermeable layers is not homogeneous, thus the clayey layers are present in the form of lentils and the water is able to leak through. In the flow systems of the sedimentary basins, the water flows through the brows and surface permeable layers towards the deep due to gravity until the potential decreases. The pressure increases in the deep, which depends on the lithostatic pressure resulting from the continuous increase of the hydrostatic pressure towards the depth, the geodynamical situation of the rock frame, and the weight of the rocks above it. In case of aquifers with bigger grain size, the grains bear the

lithostatic pressure almost by themselves, thus it affects the water body to a smaller extent; this impact is significant in case of aquifers with small grain size. The increased pressure can press the water upwards, if the upper parts have smaller potential. The upward leaking is helped by evaporation as well, as the water evaporated from near-surface layers is replaced with water from lower levels spreading as a chain reaction (Kőrössy, 1984). The geometry of the reservoir's sedimentary system has an important role in the formation of subsurface flow systems. We can understand the role of the sedimentary system's geometry with the help of the Tóth model of the uniform basin.

The consequences of the difference between the infiltration or alimentation area and the outflow or extraction area caused by the different sign of the pressure gradient. The potential drops towards the deep in the infiltration areas, thus the deeper we drill, the lower the equipotential line of the well, and the hydraulic rise height will be lower. In areas with negative pressure gradient, the water is able to flow only downwards, thus only waters younger than and with a chemism similar to surface reservoirs or precipitation can flow to deeper regions. The opposite is valid for areas with positive pressure gradient. The deeper we drill, the higher the stationary water level will be, thus the well reaches an equipotential line with a higher potential. In these circumstances, the water flows upwards towards places with lower potential, thus from bottom to the top we find older waters with a chemism similar to deeper layers.

These two areas can be observed on the Serbian side as well. Local outflow and inflow areas can be observed in smaller territory parts; however, the Pannonian aquifers are not influenced by these flows. The natural flow directions can be significantly modified by artificial water extractions and injections. The water shortage in the environment of the production wells causes a sudden drop of the potential, a depression cone is formed and the refilling of the area is started, which can significantly modify the original flow system. An annual play of water levels can be observed in the deep wells of the Great Plain to a depth of 1000 m, which is similar to groundwater, where this is regulated by infiltration-evaporation. It is certain that the subsurface waters of the Great Plain are constantly moving in a slow cycle. However, the depth and speed of the replacement are uncertain (Kőrössy, 1984). In 1976, Mihály Erdélyi divided the Pannonian Basin from a hydrodynamic point of view into a shallow and a deep flow regime. The flow system closer to the surface is gravitational, and spreads from the surface until the bottom of the Pannonian formations. The deeper system has a significant overpressure, due mainly to a regional compression (Grenerczy et al., 2000). The clayey and marly Lower Pannonian formations covering the lower flow system have a very bad permeability, thus they isolate the water body with overpressure below them. The transition between the two systems is sharp, a rise in pressure of 15-20 MPa can occur at 10-20 metres.

The geology of Vojvodina

The territory of Vojvodina is organically connected to the territory of the Hungarian Great Plain. The development of the two regions was parallel and similar. The most southern and furthest basin of the Pannonian Sea was situated on the territory of N-Vojvodina. Accordingly, the geothermal and hydrogeological features of the Vojvodina are similar to those of the Great Plain, since they are divided only politically.

The territories of Vojvodina were flooded for the first time in the Badenian stage, thus marine sediments (mainly marl) were dominant. Due to the intensive tectonic activity at the end of the Middle Miocene, the Pannonian Basin started to become delimited from surrounding territories, which continued in the Upper Miocene. Accordingly, the separate blocks could sink even 200 metres, fact that created the proper conditions for the trapping of crude oil and natural gas. The *Upper Miocene* (Pannonian – Pontian) sediments are represented by thick layers formed in decreased salt-water circumstances that are disturbed by thinner or thicker pelitic layers. During the Pliocene, the tectonic movement continued and allowed the formation of freshwater and lacustrine sediments in the Paratethys basins. A certain horizontal tectonic activity can be observed in the blocks, as a consequence of which, upcast and compression forces played an important role in the development of the Pannonian Basin. Weaker radial displacements occurred at the start of the Quaternary, as a result of which the lakes in the small basin parts recessed, filled up and some areas emerged. Freshwater, lacustrine sediment formation was slowly replaced by fluvial, Aeolian and other formations.

The features of the Pannonian sets in the region of Palic and Kanjiza

Pannonian sediments can be found on the entire research area, their thickness varies in Palic between 700 to 1,100 m, and between 200 and 1,450 m in Kanjiza.

The average thickness of *Lower Pannonian* layers reaches 200-450 metres (Palic), and 500-700 metres (Kanjiza). They deposed under shallow and salt-water conditions, on a constantly sinking base. Their lithological composition is monotonic, they contain mainly grey-green marl, smaller sand and clay bastards. The lower parts contain sandy marls, the upper ones thin sandstone, aleurolite and coaly clay lines in the form on lentils. The dominant materials of the series are the marls.

The size of watery areas decreased in the *Upper Pannonian* era. Another important event is the sweetening process of waters. The limits of the Lower and Upper Pannonian is well developed and easy to identify. The Upper Pannonian sandstone bodies contain marly, coaly-clayey lentils. The proportion of the sand grows from the bottom towards the surface. The thickness of water-bearing sandstone layers changes between 15 and 20 metres. The average thickness of *Upper Pannonian* layers reaches 150-300 metres (Palic), and 260-420 metres (Kanjiza).

The Serbian nomenclature differentiates a so-called *paludal* layer, which shows a close relation to the Levanian layers used in the Hungarian nomenclature. It covers basically the lacustrine and fluvial sediments in the partial basins of the Partethys separated during the Pliocene. The transition between the Pannonian and Quaternary was slow and gradual. The lacustrine, marshy environments grew and receded, resulting in sets of multicoloured clay, sand and aleurolite. These lay concordantly on the Upper Pannonian layers, and their separation is hard due to the lack of fossils. Coaly bastards are frequent. The thickness of water-bearing sandstone layers changes between 10 and 15 metres.

Hydrogeological features of Vojvodina, with special regard to the types of thermal water-bearing sets

The majority of the subsurface water treasure and 100% of the thermal water of Vojvodina can be found in confined aquifers. This type formed in the Quaternary and Levanian (paludal) era, and in the Pannonian sandstone, and it is also represented in the sandy, conglomerate sets of the Miocene and Lower Triassic. Within the Quaternary formations, several sand bodies formed under the depth of 70 m, the dominant fraction being the fine- and medium-grained sand. Their thickness moves between 10 and 20 metres, and they have an excellent water-holding capacity. The complete population of Northern Backa is supplied with water from these layers. Every well of the research area filters the sandy sediments of the Quaternary and Upper Pannonian. The Levanian (paludal) layers are built from clayey-sandy sediments. The series of strata contain clays, sandy clays, clayey sands and sands with different grain sizes. In case of a proper drilling technology, a yield of 10-15 l/s can be produced. The sandstones in the shallowest parts of the Levanian (paludal) layers together with the Quaternary sands supply freshwater, thus the domestic water for the population. In the sandstone layers at a depth of 600 metres, we find waters with higher salt content and temperatures. The thermal waters can have a max. temperature of 45 ^{0}C, and a max. salt content of 3 g/l. The main thermal water base can be found in the Upper Pannonian sands and the loose sandstone layers. With their appropriate physical and chemical features, they can allow a multipurpose utilization. They consist of several water-bearing layers at different depths, their thickness reaches 10-15 m. They are built from fine- and medium-grained sand with good filtration features. They accumulate a significant quantity of thermal water. Partially confined aquifers can be found in Vojvodina too, mainly connected to karst rock that hide a significant thermal treasure. These can be found in the heterogeneous sediments of the Miocene and the Lower Triassic. Considering the geological, structural and hydrogeological conditions, a thermal water reservoir with unique features was formed in these two stratigraphical units, with thermal waters with increased salt content and temperature.

The geothermal features of Vojvodina

Vojvodina is a territory with higher geothermal gradient than the European average (3.33 ^{0}C/100m). According to a high number of analyses, the geothermal gradient in Vojvodina moves between 4.5 – 7.5 ^{0}C/100m. The temperature influence is higher in Syrmia and Backa than in the Banat region. The highest geothermal gradient (6 – 7.5 ^{0}C/100m) can be observed in the areas of Backa and Syrmia, where Triassic limestone and dolomite can be found in the base of Tertiary sediments, and where convective heat transport is characteristic. Such areas are Fruška Gora and the mountain at Vrsac, where crystalline slate and magmatic rock can be found close or on the surface. The average geothermal gradient in the regions of Palic and Kanjiza is of 6 ^{0}C/100m.

The Examined Hungarian-Serbian Border region

The delimitation of the model area was executed according to the regulations of the Water Framework Directive regarding the boundaries of porous subsurface water reservoirs. The model wishes to provide an exact picture on the southern water reservoir of the Tisza River's catchment area (p.2.11.1) and the reservoirs in the Lower Tisza Valley (p.2.11.2), and the NE part of the subsurface reservoir connected to the Hungarian ones on Serbian side (CS_DU 10).

The 2852-km^2 model area was delimited in areas, where the thermal wells filtering the Pannonian layers are the most frequent in the border region. The territory can be found on the W part of the Pannonian Makó-Hódmezővásárhely trench, as a Neogene part of basin.

Available basic data

The well data were obtained from the ATIVIZIG and the database of the Subotica Waterworks. The chosen wells are presented in **table 1.** The wells filtering below the Quaternary-Upper Pannonian boundary were placed in the model. Two wells from Subotica are an exception, since they filter the lower aquifer of the Quaternary, but their huge yield significantly affects the top Upper Pannonian aquifer. The impacts of the potable water wells were modelled with well insertion at the top of the Upper Pannonian.

Filtered layers	Wells	EOV Y	EOV X	Well yield (m^3/day)
A3	Subotica1	694456	87429	1200
	Subotica2	700090	83817	1400
	Tiszasziget	737093	92851	650
	Anna-well	734900	101800	600
A5	Szeged	736300	106600	1350
	Szeged	736500	105500	1900
	Szeged	735679	101573	2000
	Kanjiza	728101	80039	232
	Domaszék	722701	100000	810
A7	Szeged	736500	105400	1350
	Palic	705142	84219	594
	Palic	705896	83472	835
	Kanjiza	728101	79052	795
	Domaszék	722701	100000	810
	Mórahalom	714785	97410	500
A9	Kanjiza	728101	78065	1631
	Szeged	728900	97300	1450
	Szeged	729200	98200	2000
	Szeged	732700	101800	1130
	Szeged	734800	100400	1540
	Tiszasziget	736807	93122	1270
	Tiszasziget	737432	92141	3000
	Üllés	714100	110900	184
	Mórahalom	714836	97243	500

Table 1. Situation, yield of the wells filtering the Upper Pannonian layers in the model area

Vertical division, sections

In order to divide the Upper Pannonian layer into aquifer and impermeable layers, 5 sections were created in which we tried to delimit the aquifers according to the filter data of the wells. The paths of the sections are presented on **fig. 6.** For the slant sections, we had to recalculate many well coordinates. The filters of the wells in the sections were defined according to the upper filter and lower filter data of the well databases, by not considering the number of filters, since the single filter data of wells with more filters were not available.

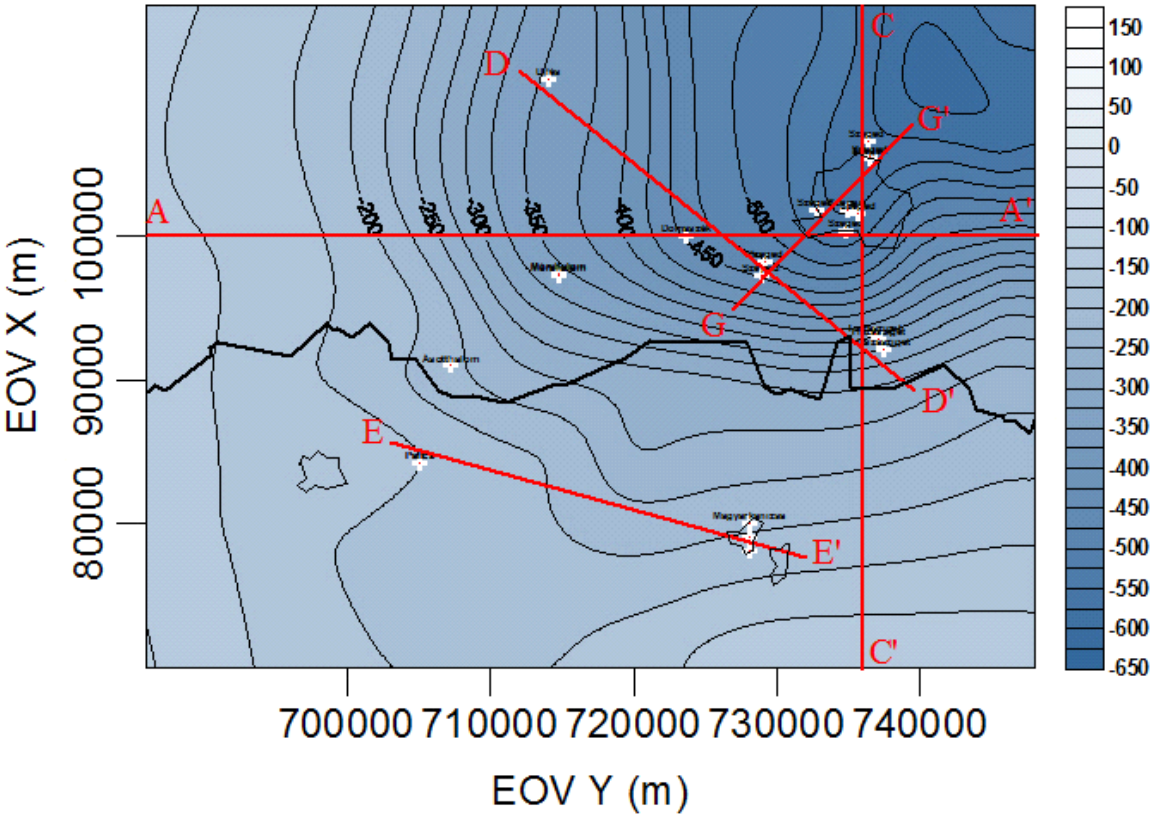

Fig. 6: The paths of sections on the contour map of the boundaries of Quaternary and Upper Pannonian layers (Source: Hajnal, 2010)

According to the available data, we delimited 6 aquifers and 5 water-barring layers. We considered the layer between surfaces A0(surface) and A1(Quaternary-Upper Pannonian boundary), symbolizing the Quaternary, for an aquifer. The area between surfaces A1 and A9 (Upper and Lower Pannonian) was considered as an Upper Pannonian set, divided into 4 aquifers and 4 water-bearing layers. According to our researches, the upper part correspond to the Zagyva Formation, divided into 2 aquifers and 3 water-barring layers, thickness ratio 1:1; while the lower 3 layers could be the Újfalu Formation, divided into 2 aquifers and 1 water-barring layers, thickness ratio 4:1. By dividing the Lower Pannonian set into 2 layers, we started with a water-barring layer and ended with an aquifer, their thickness ratio is 2:1. Since the research was meant to divide in detail the Upper Pannonian set, we considered that the division of the Lower Pannonian set into two layers was sufficient from the point of view of the model.

The presentation of the hydrodynamic model and the scenarios, and their evaluation

Hydrodynamic model

During modelling, we created a 62 km * 46-km grid, divided into cells of 500 * 500 metres, resulting in 164 lines and 188 columns. The grid was compressed into 100*100-m cells in the areas of the wells. The corner point coordinates of the grid are presented in **table 2.**

EOV Y	EOV X
686000	70000
686000	116000
748000	70000
748000	116000

Table 2: The corner point coordinates of the grid [m].

The model area was vertically divided into 11 layers (**fig. 12).** The system was originally created for the modelling of the Upper Pannonian set, but in order to secure a connection towards the adjacent Lower Pannonian and Quaternary layers, we applied three more modelling layers. The model area starts with a Quaternary aquifer with constant pressure (A1). The main theme of the modelling, the Upper Pannonian set was divided into 4 aquifers and 4 water-barring layers according to the sections mentioned earlier. The set begins from the top with a one-unit thick water-barring layer (A2), followed by a two- unit thick aquifer (A3), and a two-unit thick water-barring (A4) and one aquifer (A5). This is followed by a one-unit barring (A6), a two-unit bearing (A7), a one-unit barring (A8), and a one-unit bearing series. The unitary thickness was calculated by dividing the thickness grid of the Upper Pannonian set, from the base to the surface, from the HUSER study into 8 parts. The Lower Pannonian set was divided into two layers, a two-unit barring and a one-unit bearing layer that is kept at constant pressure (100m).

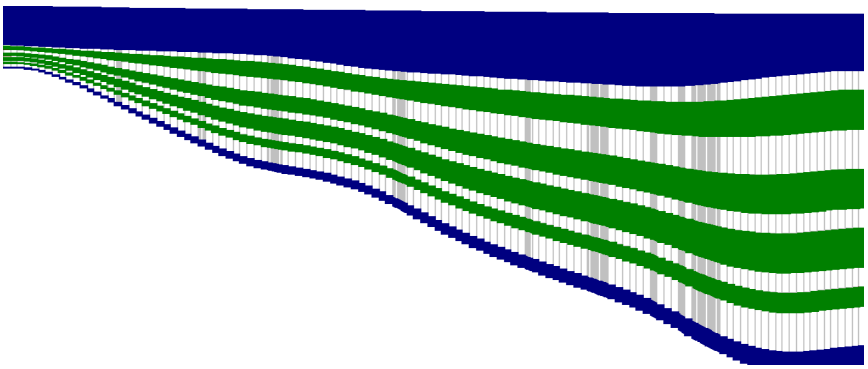

Fig. 12: Vertical division of the model area; the aquifers are coloured, the green ones are the Upper Pannonian layers. (Source: Kárász, 2010)

Filtration coefficients

The horizontal and vertical filtration coefficient values were defined according to literature data (Szanyi et al.). The filtration coefficient of layers is presented in **table 3.**

Free porosity

Porosity values were defined according to the empirical functional relationship between the filtration coefficient and the effective porosity (Szanyi, 2009). The functional relationship between the filtration coefficient and the effective porosity:

$$\ln(n_0) = 0.1363871237 \cdot \ln\left[k(m \cdot d^{-1})\right] - 1.971624126$$

The free porosity values in the modelled layers are presented in **table 3**.

Number	Layer	Age	Filtration coefficient [m/day]		Free porosity [-]
			horizontal	vertical	
A1	Aquifer	Q	1.54	0.0032	0.2
A2	Water-barring	Pa_2	0.0095	0.000085	0.1
A3	Aquifer		1.04	0.0017	0.18
A4	Water-barring		0.0095	0.000085	0.1
A5	Aquifer		1.04	0.0017	0.18
A6	Water-barring		0.0095	0.000085	0.1
A7	Aquifer		1.04	0.0017	0.15
A8	Water-barring		0.0095	0.00085	0.1
A9	Aquifer		1.04	0.0017	0.15
A10	Water-barring	Pa_1	0.0057	0.000025	0.1
A11	Aquifer		0.62	0.00093	0.13

Table 3: Main features of modelled layers.

Boundary conditions

In the model, we used GHB cells where necessary. Since the lateral boundaries of the model did not coincide with the reservoir boundaries, the application of boundary conditions was necessary. We secured the filtration in the vertical, gravitational system with the boundary conditions in model layers no. 3, 5, 7 and 9.

The GHB-type of boundary conditions allows changes in the pressure level in the boundary cells, by changing the water balance of the cell in proportion with the developing depression. In these elements, the amount of water between the boundary and the adjacent cell is defined by a proportionality factor and the difference between the water level in the cell adjacent to the boundary and the fictional water level given for

the boundary.

The higher the proportionality factor and the water level difference at the boundary of the model, the bigger the amount of the fed or drained water. The GHB cells can be used with an infinite proportionality factor, constant pressure level, zero factor, as a water-barring boundary.

We used GHB cells of different strength values that allow lateral supplies of different amounts.

The GHB values in the table can be realized in the western part of the model area, if we hypothesize a constant-pressure boundary at a distance of 5,000 metres from them. The distance in the eastern part is of 25,000 metres.

The presentation of scenarios

Four production conditions are examined during modelling:
- natural condition without wells, with the definition of the pressure level of the aquifer according to the geometry and geology of the territory,
- current condition with producing wells,
- probable future condition with producing wells in case of an increased heat demand (increase of well capacities by 25%),
- probable future condition with producing wells in case of an increased heat demand (increase of well capacities by 50%),

In case of the current condition, we calculated with a water production estimated according to the water production declared by water users and authorized for the single wells, and by assuming an annual production with constant yield. This means a thermal water production of 28.5 million m^3/year in the model area.

In case of the probable future condition, the current yield of the wells was increased by 25 and 50%. The increased water production did not result in a drop of pressure in the modelled area, since reinjection increased in parallel with the increased production.

Evaluation of scenarios

After the calculations, we examined the drawdown values and water level data experienced in the Upper Pannonian aquifer by different circumstances. The objective of the analyses was the definition and delimitation of the biggest current and future drawdown areas. The maps of examined areas are presented **on fig. 14-16 of Annex 1.**

- By current production, the drawdown curves look as follows in layers no. 3, 5, 7 and 9 (**annex, fig. 14).**
- In the probable future condition, by a capacity increase of 25%, the drawdown curves look as follows in layers no. 3, 5, 7 and 9 (**annex, fig. 15).**
- In case no. 3, by a capacity increase of 50%, the drawdown curves show progressively increasing values compared to the previous scenarios in layers no. 3, 5, 7 and 9 (**annex, fig. 16).**

The contour maps show that the model indicates the expected drop of the pressure level and the increase of the drawdown towards the growing water productions.

Monitoring system

For the evaluation of probable conditions, we suggest a network of monitoring wells within the model area on both sides of the border for the monitoring of piezometric levels and drawdown values.

The monitoring network is a system of well groups with 4 wells each, where one well is opened in every Upper Pannonian aquifer. Two groups of such wells were planned for Hungary.

Monitoring wells	EOV Y	EOV X	Layer	Drawdown without wells	Drawdown with wells	Drawdown + 25%	Drawdown + 50%
Hun1	736443,9	97060,69	A3	0	2,905141	3,596991	4,316391
Hun2	736443,9	97160,69	A5	0	9,738641	10,59683	12,71619
Hun3	736443,9	97260,69	A7	0	10,8341	11,29191	13,55029
Hun4	736443,9	97360,69	A9	0	19,71891	25,40958	30,4915
Hun5	728749,6	101951,3	A3	0	2,877591	3,631431	4,35772
Hun6	728649,6	101951,3	A5	0	8,47746	12,1733	14,60795
Hun7	728549,6	101951,3	A7	0	9,033527	13,54263	16,25115
Hun8	728449,6	101951,3	A9	0	20,32767	24,64864	29,57836

Monitoring wells	EOV Y	EOV X	Layer	Water level without wells	Water level with wells	Water level+ 25%	Water level + 50%
Hun1	736443,9	97060,69	A3	89,08316	86,20557	85,48617	84,76677
Hun2	736443,9	97160,69	A5	93,98522	85,50776	83,3884	81,26903
Hun3	736443,9	97260,69	A7	96,16387	87,13034	84,87196	82,61358
Hun4	736443,9	97360,69	A9	97,60215	77,27448	72,19257	67,11065
Hun5	728749,6	101951,3	A3	91,45473	88,54958	87,8233	87,09701
Hun6	728649,6	101951,3	A5	96,12296	86,38432	83,94967	81,51501
Hun7	728549,6	101951,3	A7	97,75954	86,92543	84,21691	81,50838
Hun8	728449,6	101951,3	A9	98,64454	78,92563	73,9959	69,06618

Table 5: Water level data of monitoring wells in Hungary for the different scenarios

The main criterion for the design location was to serve the monitoring of the biggest load, i.e. of the depression area. The parameters from the monitoring wells can be seen in **tables 2 and 3,** and in the water level and drawdown diagrams – **annex, fig. 18-19** - presenting impact of the increasing production.

Monitoring wells	EOV Y	EOV X	Layer	Water level without wells	Water level with wells	Water level +25%	Water level +50%
Srb1	700044,8	87251,38	A3	111,6651	107,3134	106,2255	105,1376
Srb2	700144,8	87251,38	A5	108,5445	103,8569	102,685	101,5131
Srb3	700244,8	87251,38	A7	107,2297	101,8764	100,5206	99,16477
Srb4	700344,8	87251,38	A9	106,2454	101,4143	100,2065	98,99876
Srb5	728651,8	87155,42	A3	93,29434	90,92497	90,33263	89,74027
Srb6	728751,8	87255,42	A5	93,04011	89,19081	87,49409	85,79738
Srb7	728851,8	87355,42	A7	97,34581	88,0741	85,75618	83,43826
Srb8	728951,8	87455,42	A9	98,18491	83,7567	80,14965	76,54259

Monitoring wells	EOV Y	EOV X	Layer	Drawdown without wells	Drawdown with wells	Drawdown +25%	Drawdown +50%
Srb1	700044,8	87251,38	A3	0	4,351683	5,439603	6,527523
Srb2	700144,8	87251,38	A5	0	4,687641	5,859539	7,031436
Srb3	700244,8	87251,38	A7	0	5,42328	6,779102	8,134924
Srb4	700344,8	87251,38	A9	0	4,831089	6,038863	7,246637
Srb5	728651,8	87155,42	A3	0	2,369373	2,961719	3,554066
Srb6	728751,8	87255,42	A5	0	6,786863	8,48358	10,1803
Srb7	728851,8	87355,42	A7	0	9,271708	11,58963	13,90756
Srb8	728951,8	87455,42	A9	0	14,42821	18,03527	21,64232

Table 6: Drawdown data of monitoring wells in Serbia for the different scenarios

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Annexes

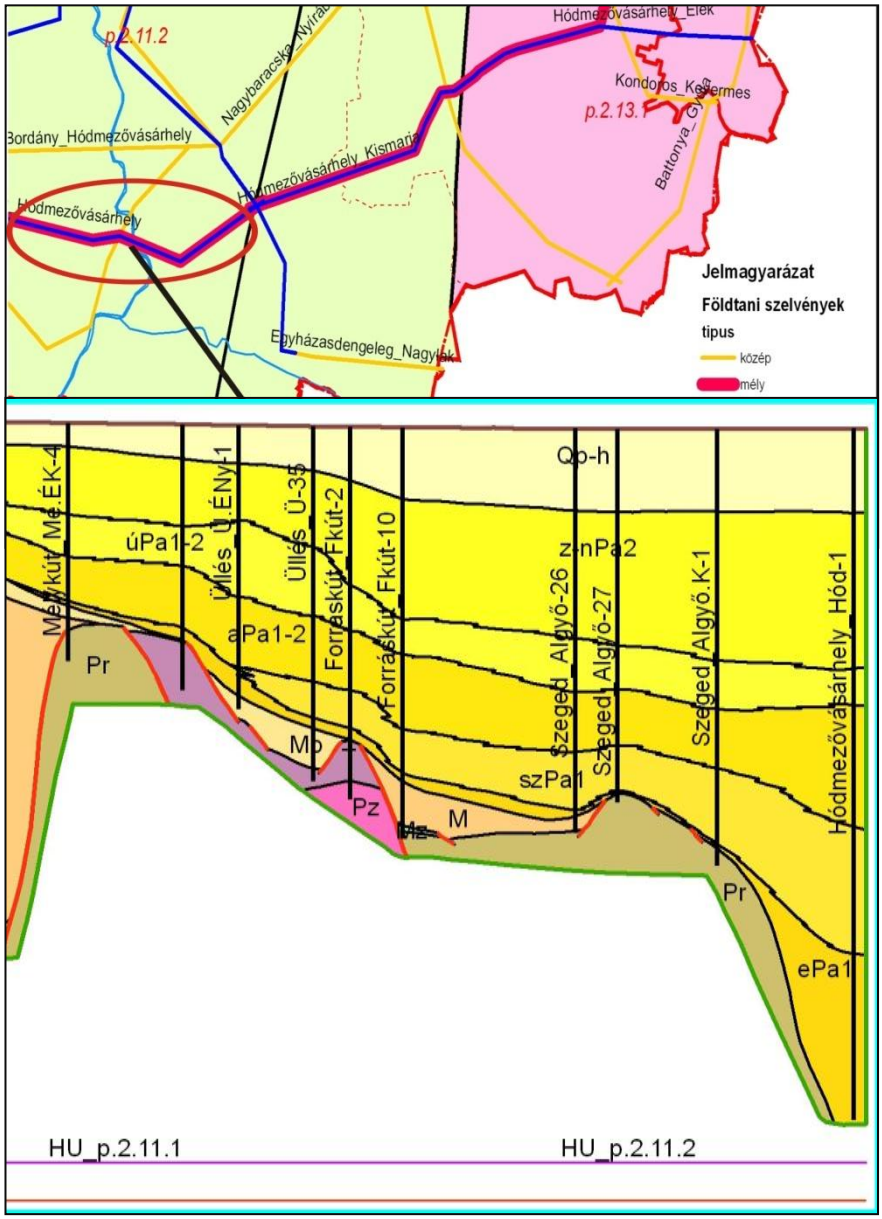


Fig. 5: The cross-section path designed by the Geological Institute of Hungary (MÁFI) (Source: MÁFI)

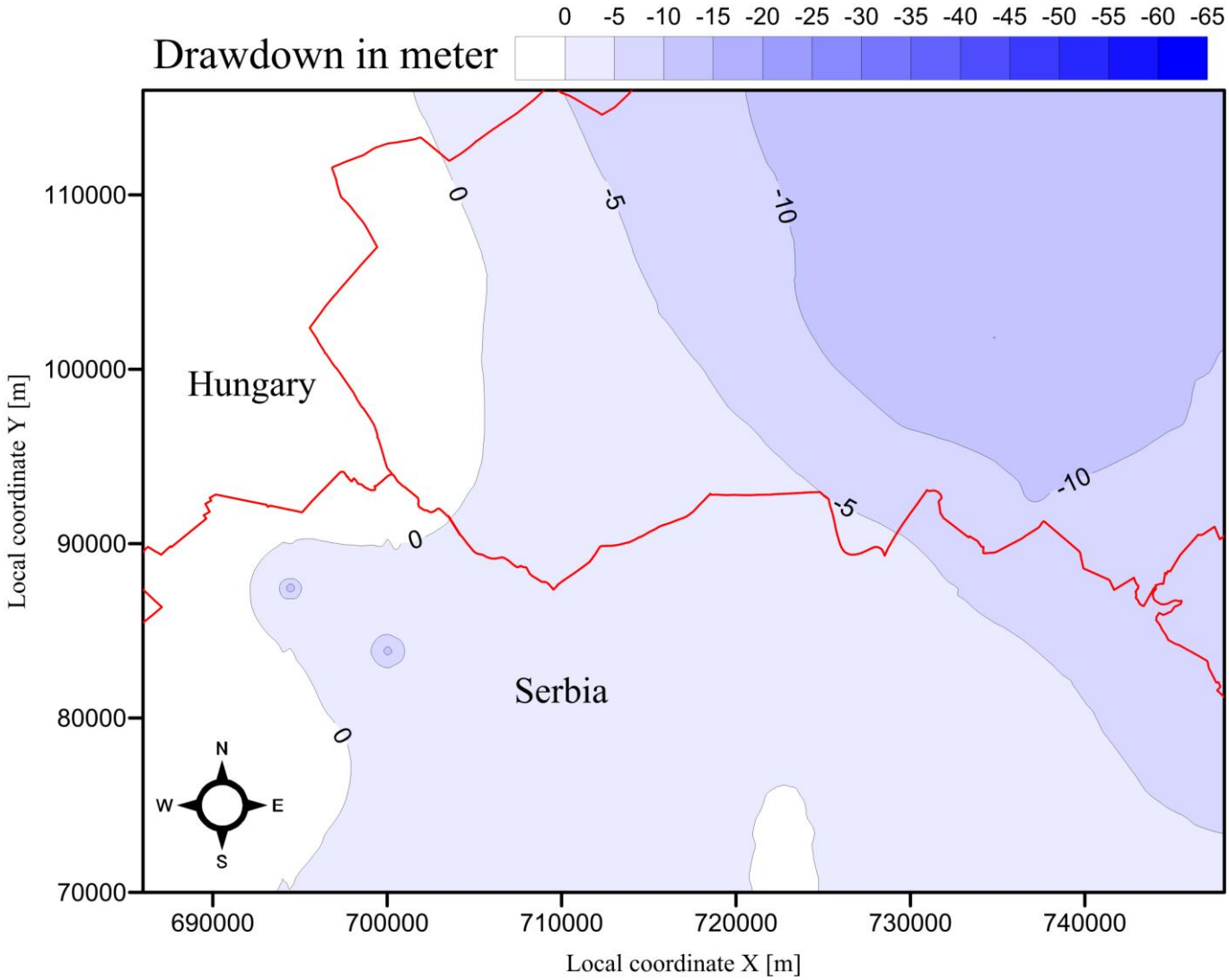


Figure: Drawdown by current water productions in the third Upper Pannonian layer, in **meter**

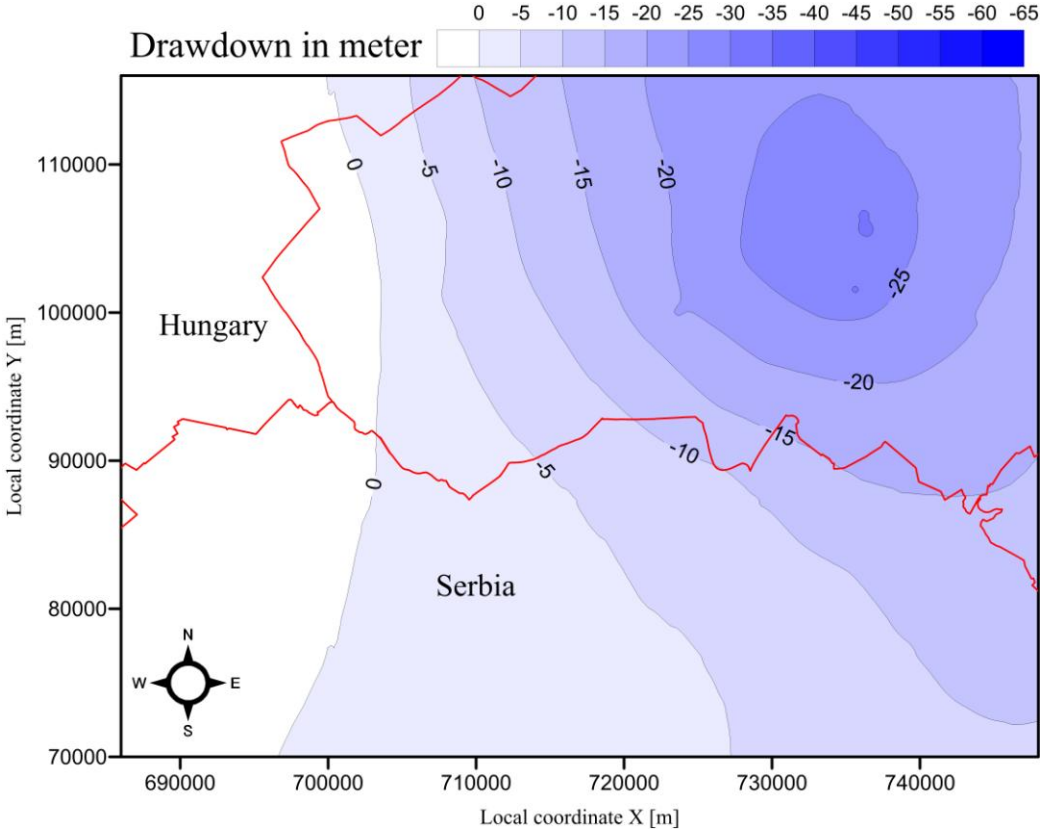


Figure: Drawdown by current water productions in the fifth Upper Pannonian layer, in **meter**

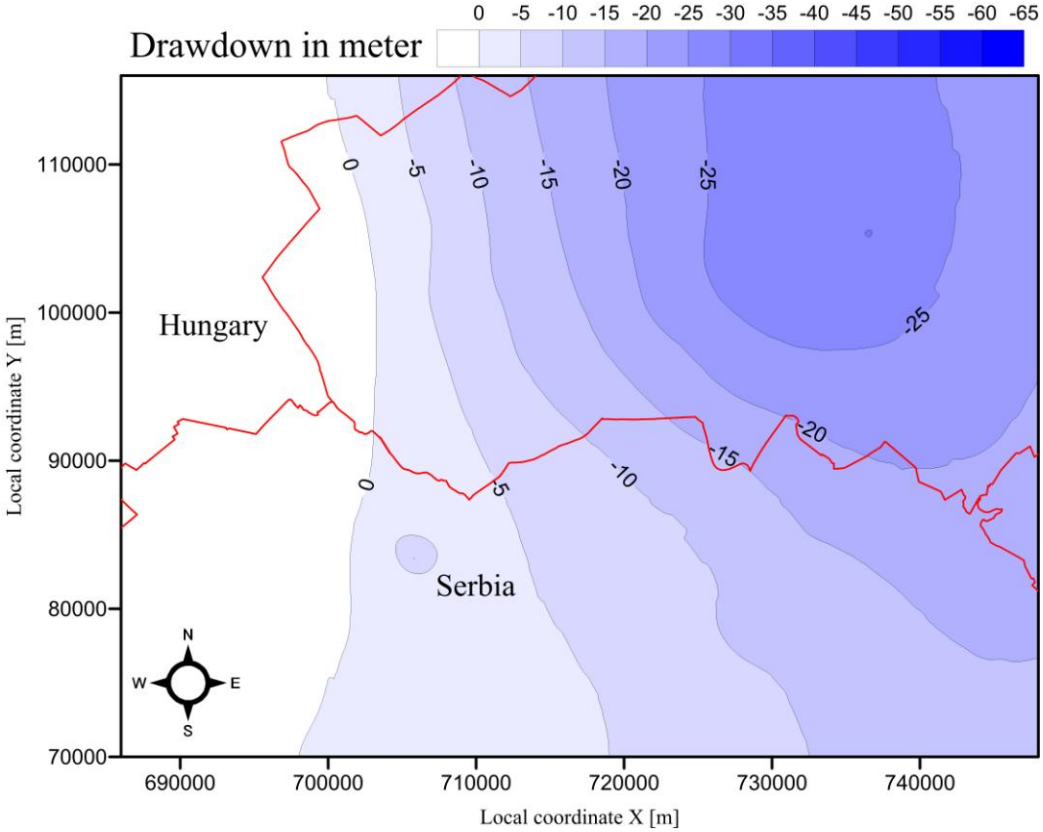


Figure: Drawdown by current water productions in the seventh Upper Pannonian layer, in **meter**

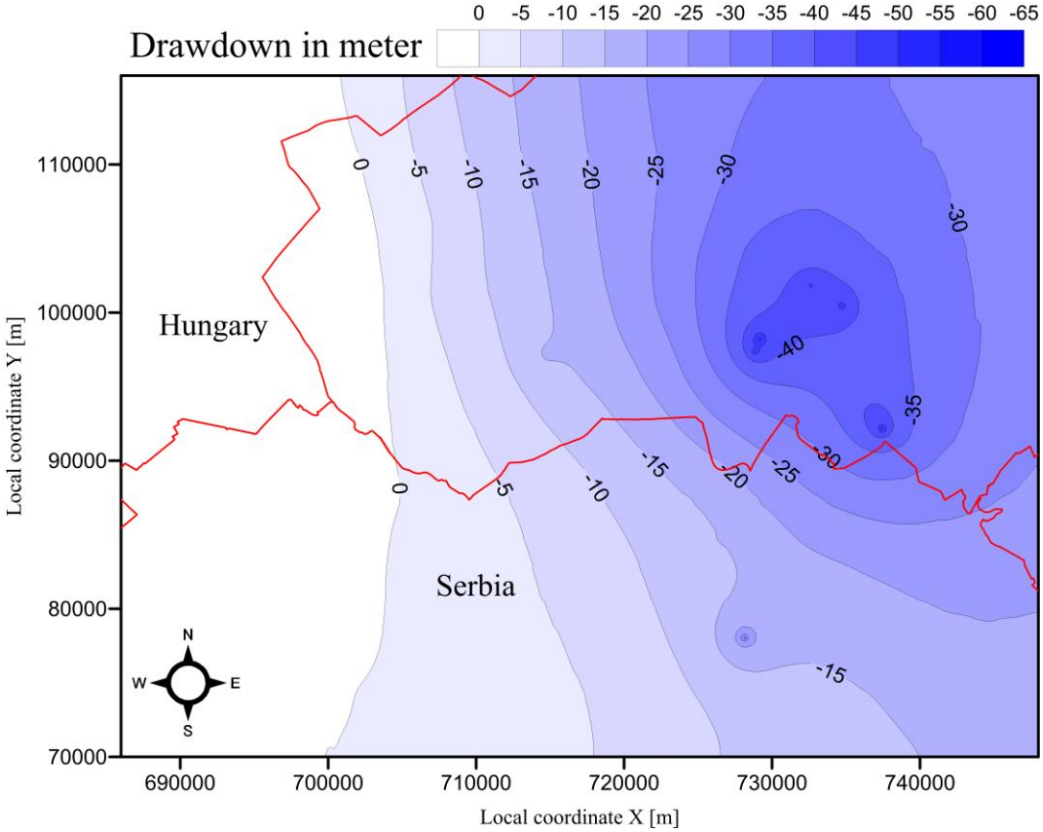
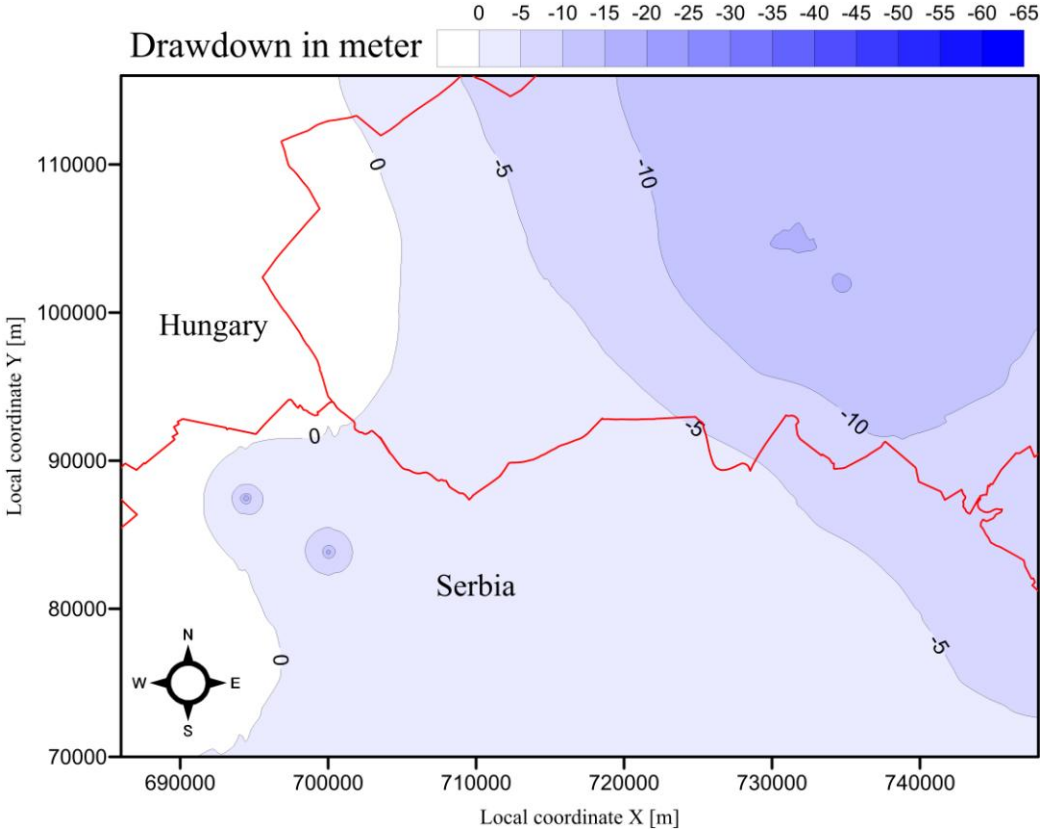
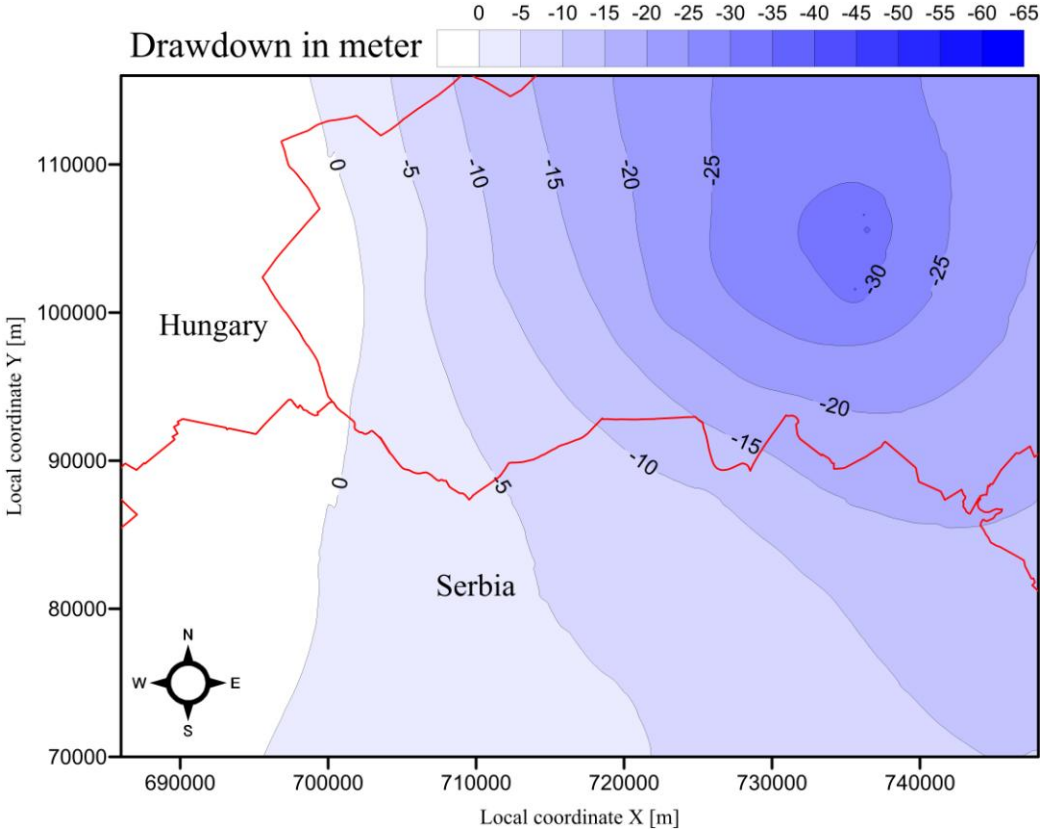


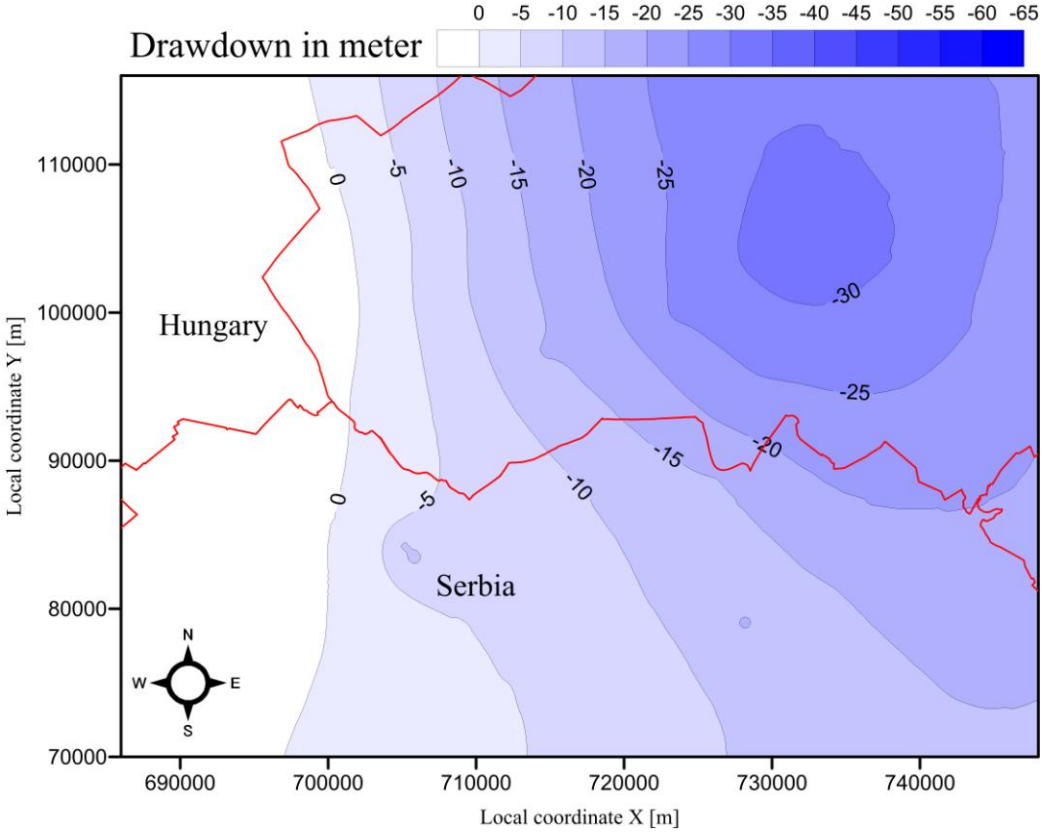
Figure: Drawdown by current water productions in the ninth Upper Pannonian layer, in **meter**



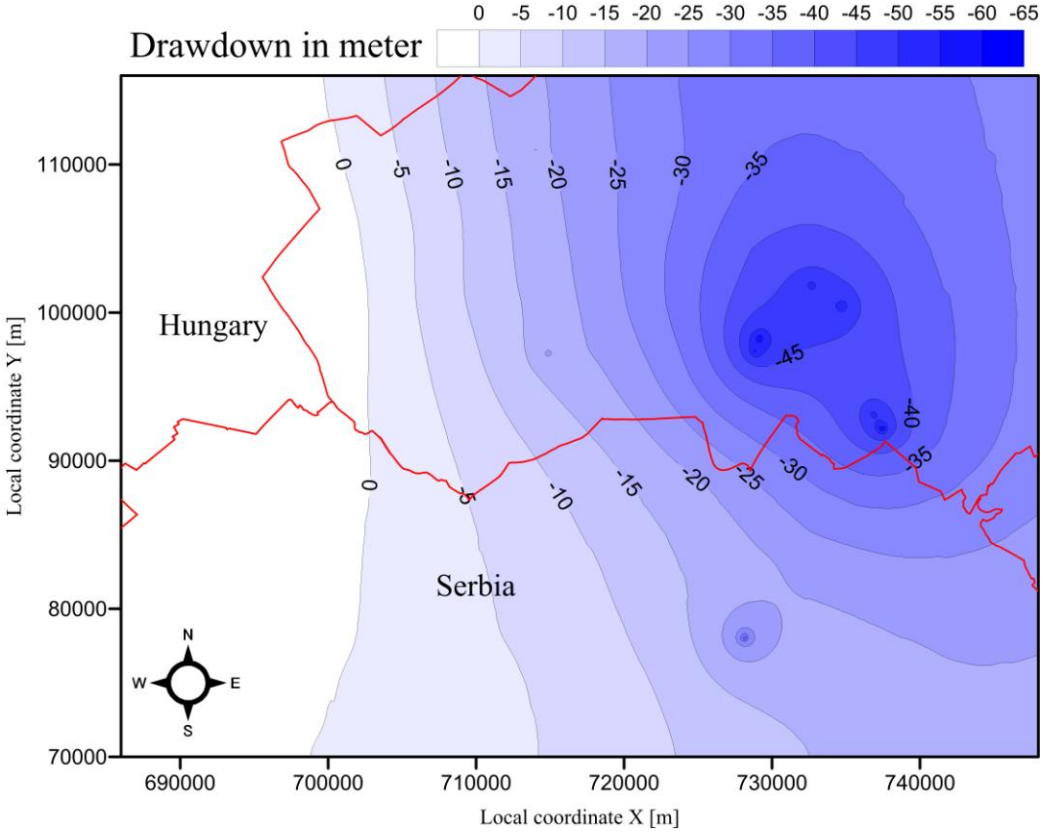
. Figure: Drawdown by a water production increased by 25% in the third Upper Pannonian layer, in **meter**



. Figure: Drawdown by a water production increased by 25% in the fifth Upper Pannonian layer, in **meter**



. Figure: Drawdown by a water production increased by 25% in the seventh Upper Pannonian layer, in **meter**



. Figure: Drawdown by a water production increased by 25% in the ninth Upper Pannonian layer, in **meter**

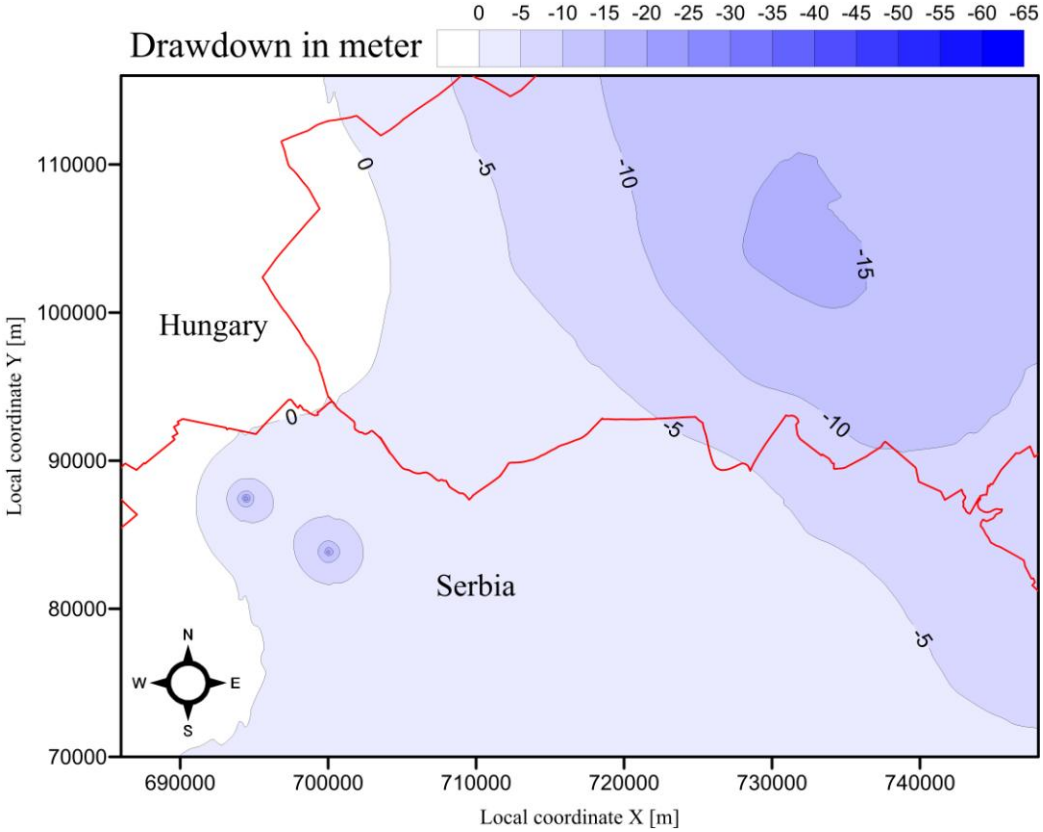


Figure: Drawdown by a water production increased by 50% in the third Upper Pannonian layer, in **meter**

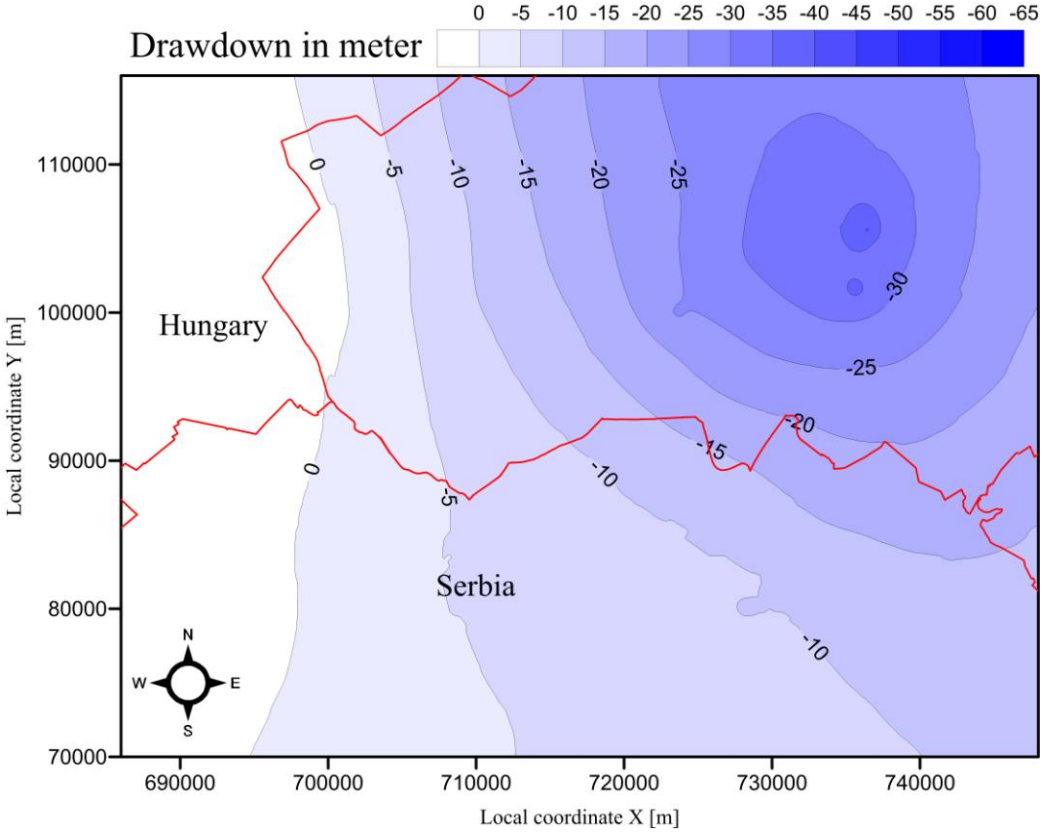


Figure: Drawdown by a water production increased by 50% in the fifth Upper Pannonian layer, in **meter**

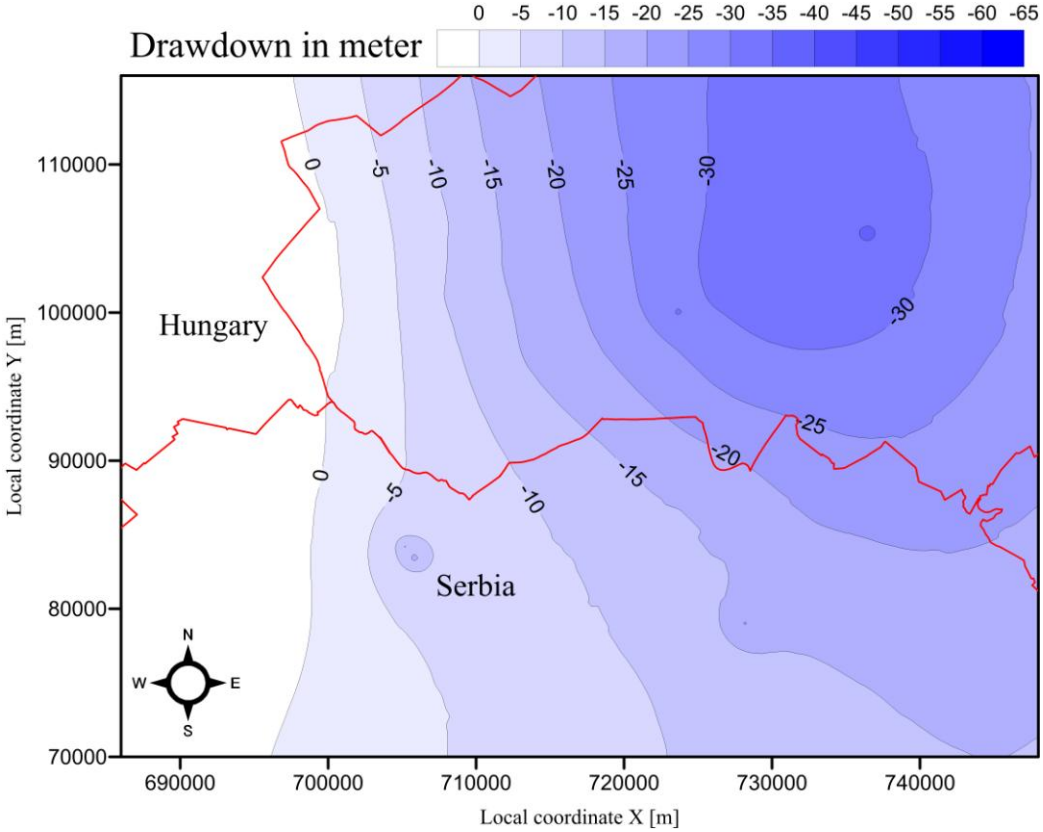


Figure: Drawdown by a water production increased by 50% in the seventh Upper Pannonian layer, in **meter**

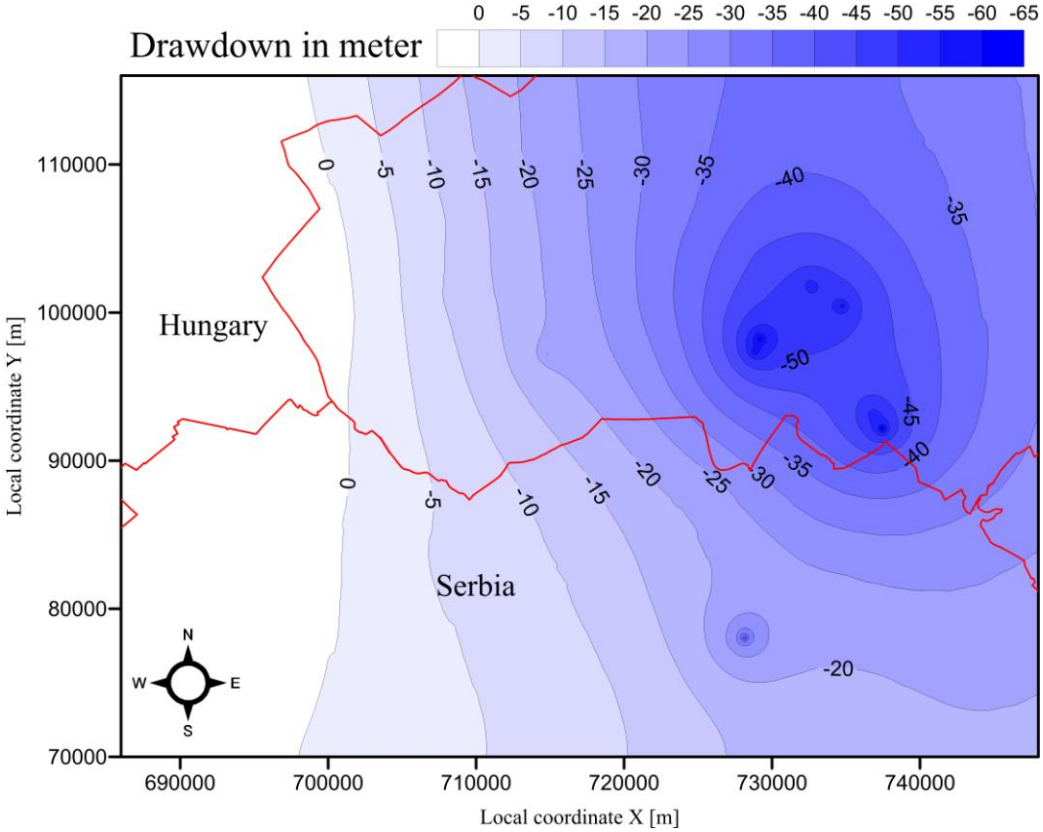


Figure: Drawdown by a water production increased by 50% in the ninth Upper Pannonian layer, in **meter**

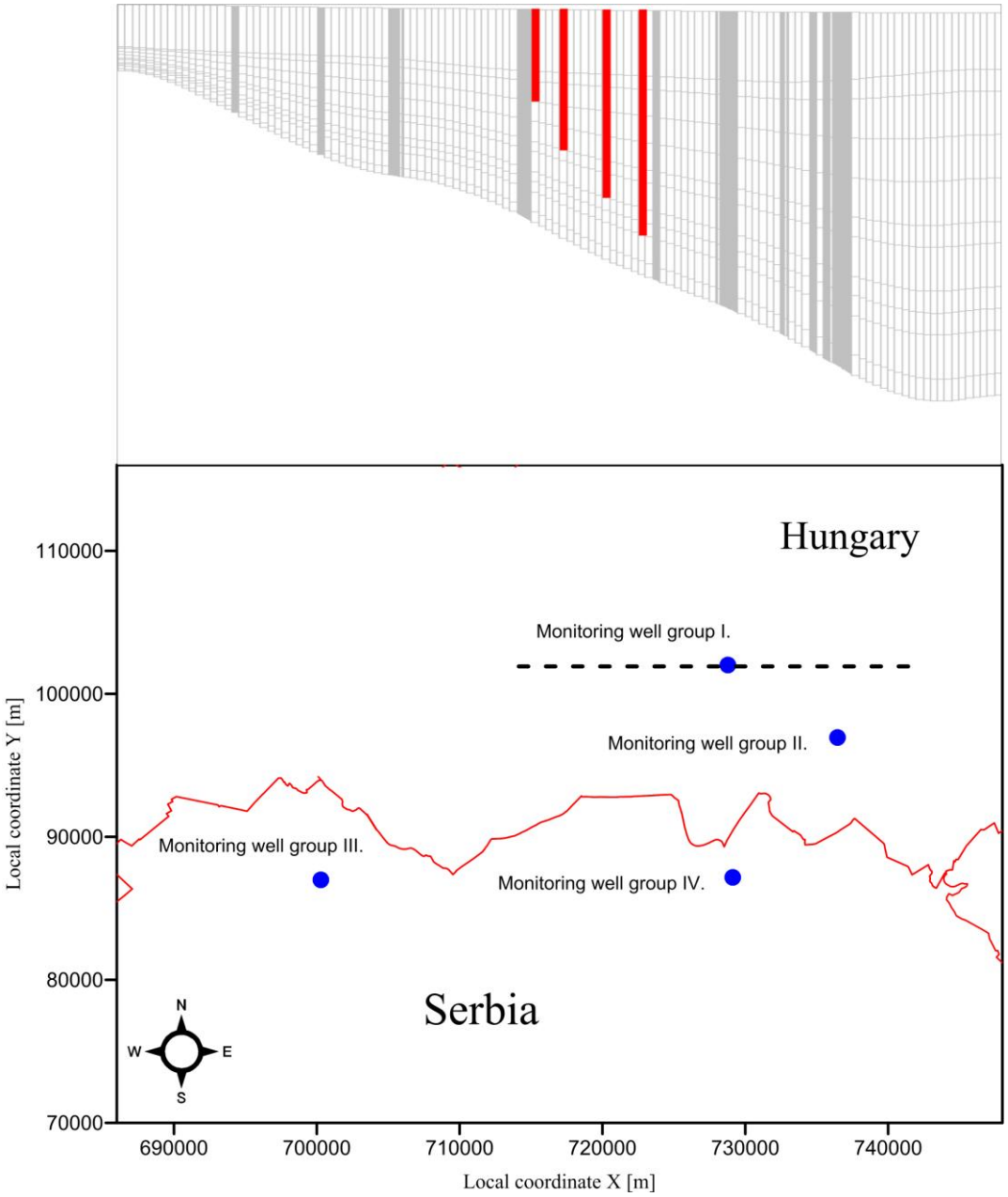


Figure: Place and depth of the monitoring wells