Summary report of the supra-regional hydrogeological model

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Date 30 September 2012

Status final

Type Text

Description This document summarizes results of the supra-regional hydrogeological model, contains the characterization of the regional groundwater flow systems, hydrogeochemistry, the boundary conditions, hydrostratigtrapgic units and the numerical model of the porous sub-system and the basement, as well as calibration targets and main model outputs (hydraulic potentials, budgets, depressions).

Format PDF

Language En

Project TRANSENERGY –Transboundary Geothermal Energy Resources of Slovenia, Austria, Hungary and Slovakia

Work package WP5 Cross-border geoscientific models
5.2.2. Supra-regional hydrogeological model

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1.Introduction

The aim of the TRANSENERGY project is to support the harmonized thermal water and geothermal energy utilization in the western part of the Pannonian Basin, which is situated in the transboundary zone of Austria, Hungary, Slovak Republic and Slovenia.

Natural resources, such as geothermal energy, whose main carrying medium are deep groundwaters along regional flow paths, are strongly linked to geological structures that do not stop at state borders. Therefore only a transboundary approach and the establishment of a joint, multi-national management system may handle the assessment of geothermal energy and the limits of use in a region, irrespective of political state borders. This is especially true for transboundary aquifers, where water extraction at a national level without cross-border harmonized management strategies may cause negative impacts (depletion or overexploitation) leading to unnecessary economic and political tensions between countries.

During the every day management of thermal-water systems, the decision makers need information about the future responses of the system on the effects of various interactions, as well as about available hydrogoethermal resources. This tool can be based on the results of different models, such as geological-, hydrogeological-, and geothermal models building on each other.

The aim of the supra-regional hydrogeological model is to give an overview on the large-scale hydrogeological processes of thermal water flow systems in the western part of the Pannonian Basin. Thus, the connection among the main groundwater bodies (that sometimes have very different geological-hydrogeological characteristics) can be determined.

The so called supra regional model includes the entire TRANSENERGY project area. The supra regional model handled this area in a uniform system approach. A steady state three dimensional groundwater flow model was constructed, calibrated, and used to describe regional flow of the project area.

2.Geographic settings

The TRANSENERGY project area is situated in the transboundary region of Austria, Slovakia, Slovenia and Hungary. This part of the Pannonian Basin is surrounded by the eastern margin of the Alps, the western margin of Carpathians, the Transdanubian Midmountains and the Slovenske Gorice. Between these mountains there are lowland regions separated with hilly territories and smaller inselbergs (island-hills) (Figure 1).

The Austrian part of the TRANSENERGY project region comprises the eastern margin of the Alps and its intramountain basins. The two most important geological basins of this region are the Styrian Basin in the southwest and the Vienna Basin in the northeast. The Styrian Basin is geographically divided by the Sausil into the small western Styrian basin and the eastern Styrian basin, which contains among others the Eastern Styrian Hill Land, the Graz Field and the Leibnitz Field. The Vienna Basin forms a transition to the Carpathians. The Mattersburg Basin in the south of the Leitha Mountains can be considered as side basin of the Vienna Basin. The Oberpullendorf Basin as well as the Seewinkel and the Parndorf plateau form a transition towards the Little Hungarian Plain (Kisalföld).

The Slovakian continuation of the Vienna Basin is the Zahorska nizina Lowland. Eastward it is separated from the Podunajska nizina Lowland by the Male Karpaty mountains. Podunajska nizina Lowland is bordered by the western margin of the Carpathian Mountains on the northern and eastern side. Towards the south the Lowland continues to the Little Hungarian Plain in Hungary.

The Little Hungarian Plain is situated in the northwestern part of the Hungarian project area. Southeastward it is bordered with the Transdanubain Midmountains, which has a continuation in the lower Zala Hills.

This hilly region is continuing towards Slovenia, in the Goricko. The central part of the project area in Slovenia is Slovenske Gorice. On the wester part it is boardered by Kozjak, Pohorje and Haloze hilly areas. Along the Drava River Drava, Ptuj and Ormož fields are found. Along the Mura River the Mura field is situated, which is bordered by the Slovenske Gorice on the southwest, and by the Goričko hills on the northeast.

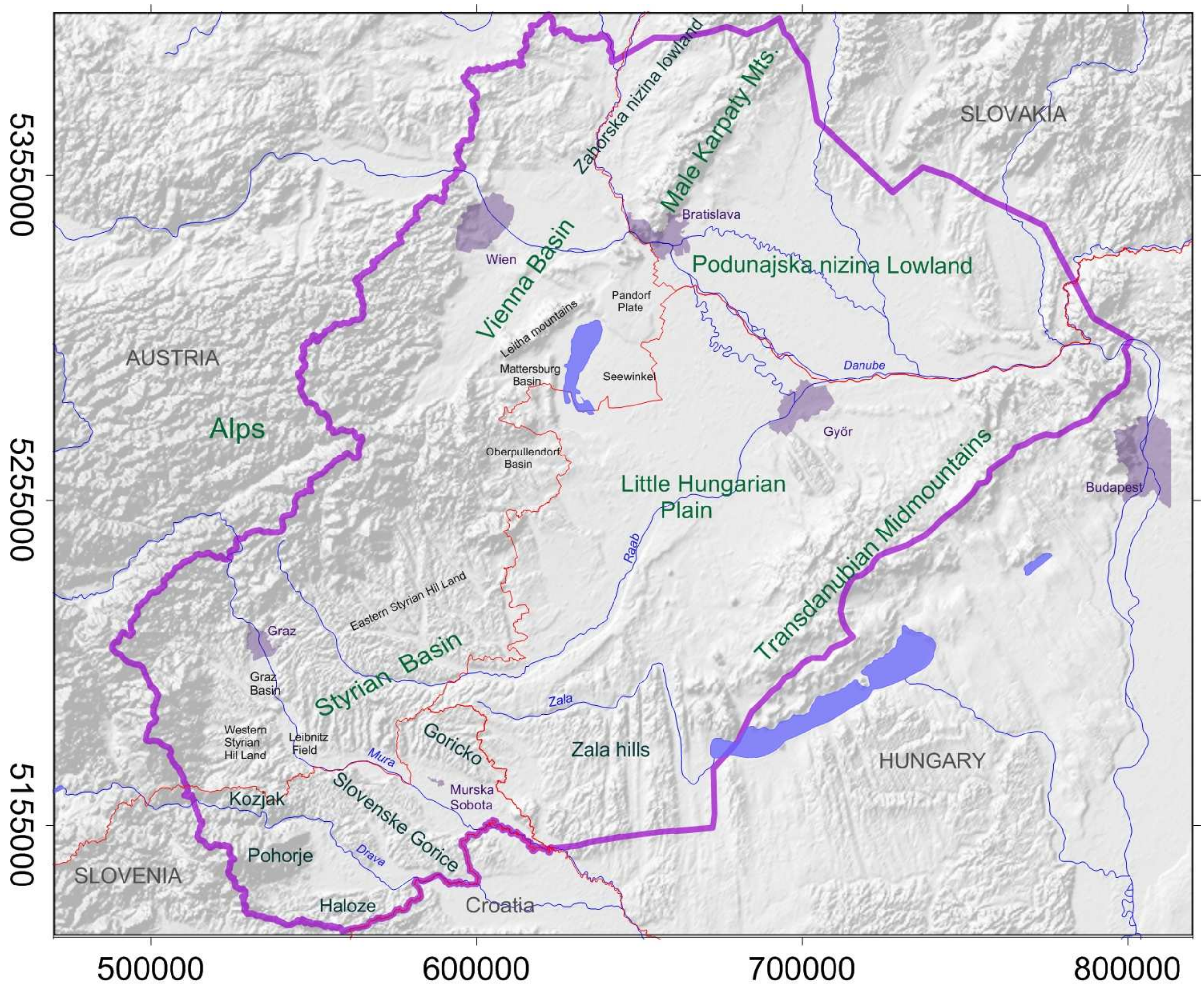

Figure 1: Main geographical units of the project area

2.1. Climate

The project area is situated in the temperate climate zone, characterized by four seasons. However the project area is situated at the overlap of three climate regions of oceanic, mediterranean and continental modified by the topographic relief and the position of basins. Approximately 1500 km far from the ocean, the oceanic effect is decreased, but the continental effect has not become dominant yet. The mediterranean effect is manifested in the precipitation distribution within a year. Due to this combined characters extremities often occur.

There is no significant spatial difference in the temperature distribution within the project area. The average temperature in January is between -2 – -4 °C and in July it is between 23-25 °C The annual distribution of temperature and precipitation under humid temperate climate is shown in Figure 2.

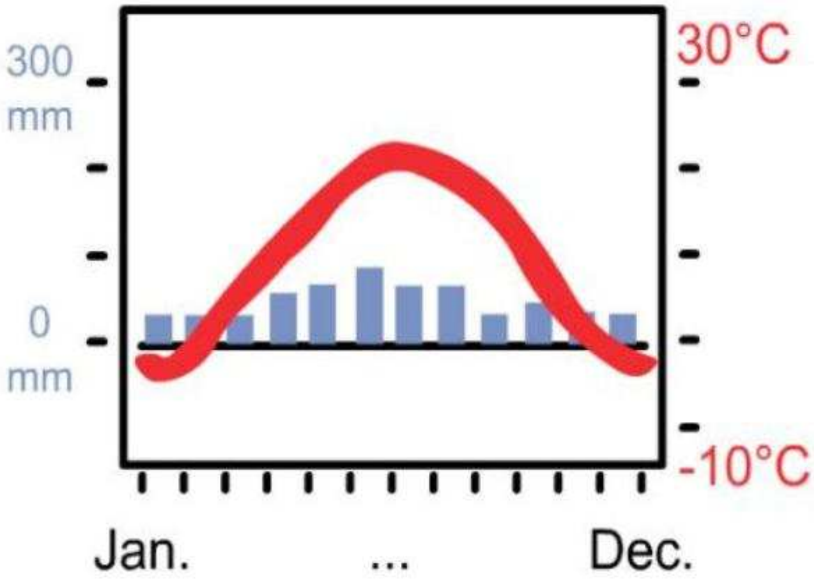

Figure 2: The average annual distribution of temperature and precipitation under humid temperate climate

The spatial distribution of annual amount of precipitation is mainly influenced by the topographical effect (Figure 3). Its value varies between 500-1500 mm. Increasing trend can be observed in the direction to southwest and and higher values occur in the mountain regions.

2.2. Morphology

The relief of the 47 700 km^2 sized supra regional area, varies between 100-2100 m. The project area is surrounded by mountains of the Eastern Alps, western part of Carpathians, Transdanubian Midmountains, Kozjak, Pohorje, Haloze mountains. Some smaller mountain regions occur inside the area, like Male Karpaty, Leitha Mountains and Sopron Mountains. As it is shown on Figure 4, majority of the region (about 71%), is lower than 300 meters and the mountains above 500 meters form only 12% of the total area. There are some hilly areas, like Zala Hills, Slovenske Gorice and Goricko (17% of total area). Table 1 shows the elevation distribution of the area.

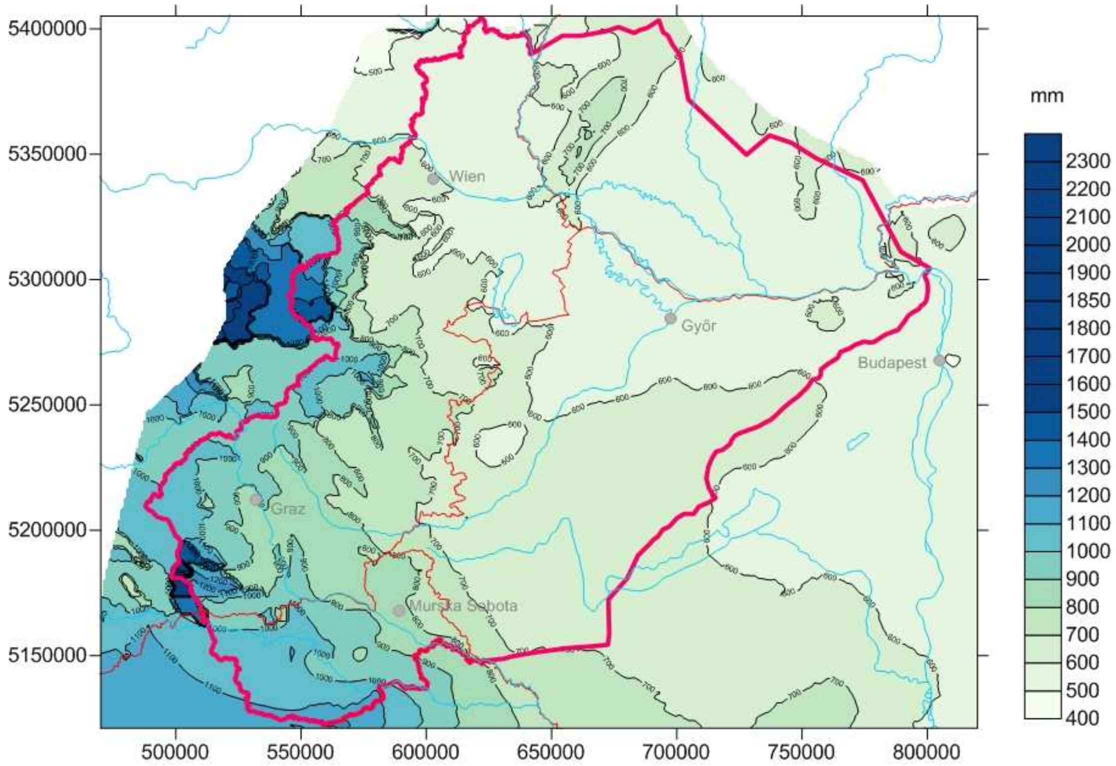

Figure 3: Spatial distribution of annual amount of precipitation

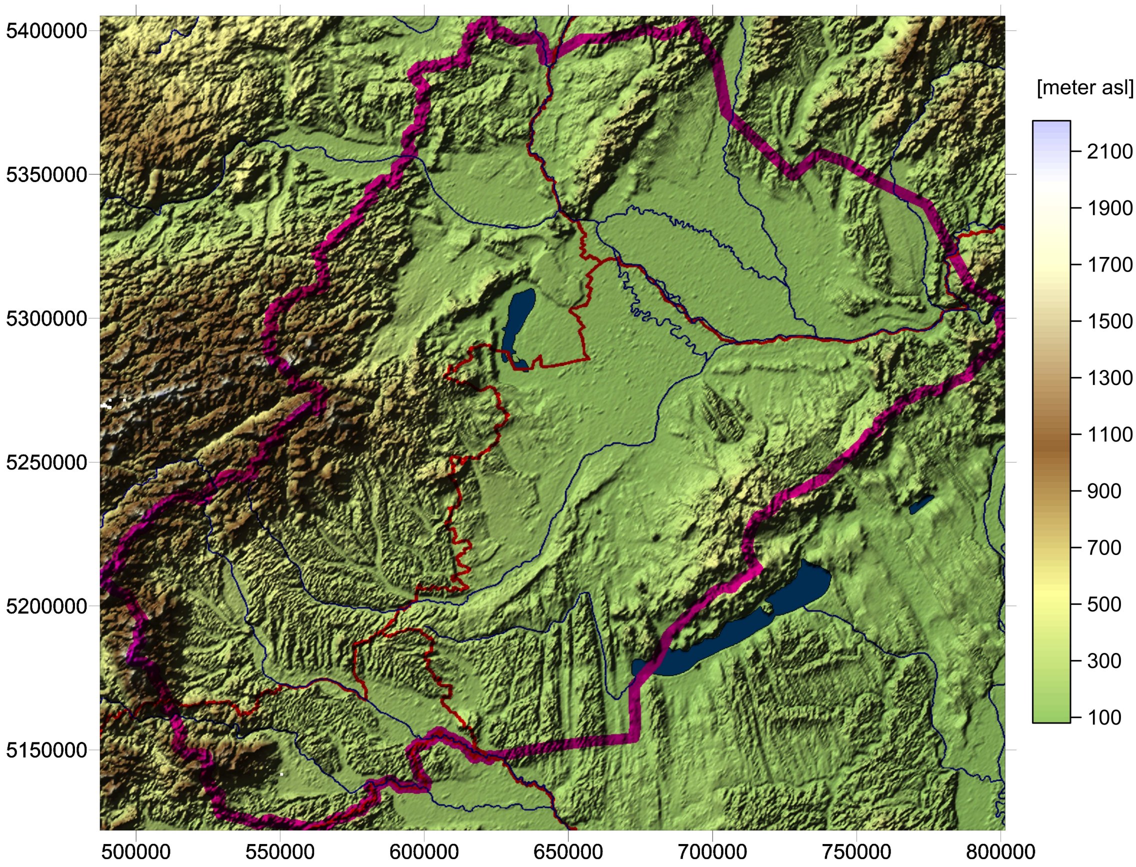

Figure 4: Morphological map of Supra-region

Table 1. Elevation distribution of the project area

Elevation interval (m above see level)	Area [km2]	Area [%]
supra area	47741.6	100
100-300	33797.1	70.8
300-400	5539.3	11.6
400-500	2652.2	5.6
500-2100	5752.8	12.0

2.3. River network

The entire TRANSENERGY project area belongs to the Danube River basin. The rivers are connected to two main river networks of the Danube and Drava. The most important tributaries of Danube are Morava, Vah, Hron, Ipel and Raba, and the most important tributary of Drava is the Mura River. The Zala river belongs to the watershed of lake Balaton which water flows into one of the tributary channels (Sió) of Danube out of the project region (Figure 5).

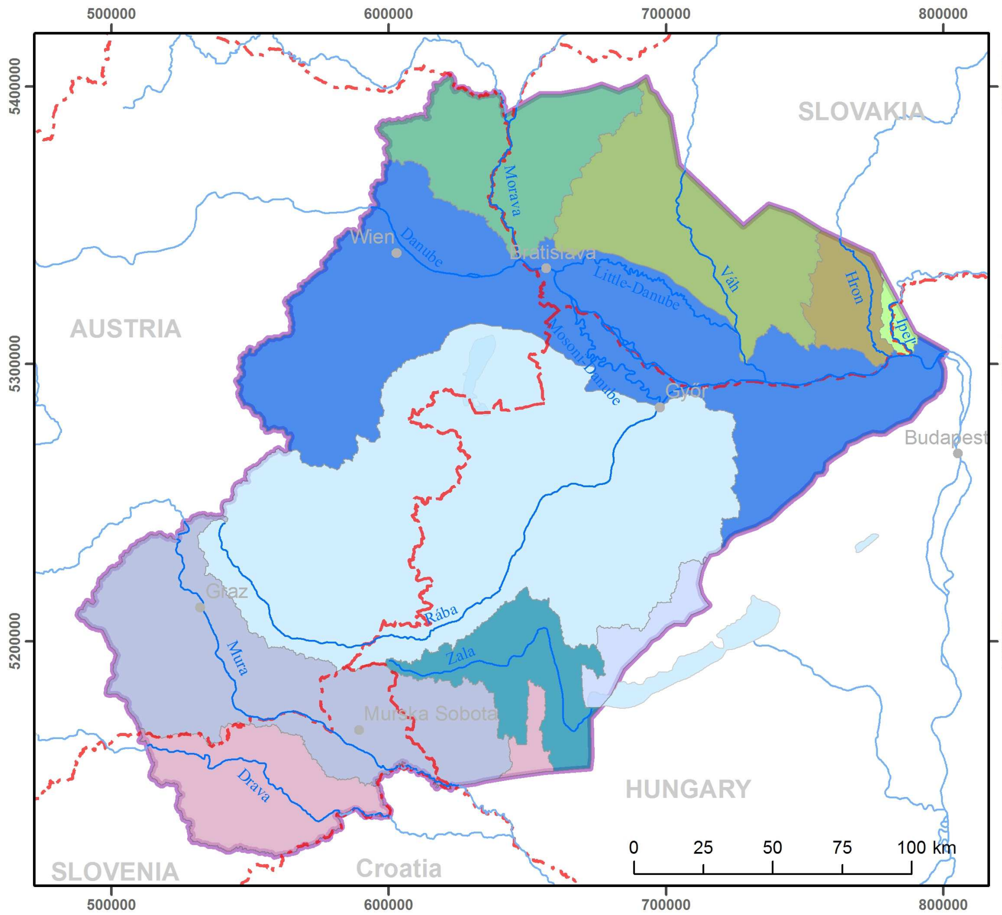

Figure 5: The most important rivers and watersheds in the project area

The total length of the rivers is about 1250 km within the supra regional area. The longest is the Raba which is about 225 km, the shortest is the Ipoly with the length of about 27 km (Table 2).

Table 2. Length of the main rivers within the project area

River	Length [km]
Ipel	27.1
Hron	55.2
Morava	70.5
Vah	93.8
Drava	107.8
Mura	169.7
Danube	245.6
Raba	255.1

3.General description of the Supra-Regional Area

3.1. Regional geology

The geology of the supra regional area is discussed in details in the summary report of geological models (Maros et al., 2012). Here only a brief summary is presented to provide a geological framework for the hydrogeological model.

3.1.1.Geology of the pre-Cenozoic basement

The studied area belongs mostly to the ALCAPA major tectonic unit (East Alpine-Central Western Carpathian-North Pannonian lithospheric segment: Ratschbacher et al. 1991a,b; Csontos & Vörös 2004). The area shows complicated geological structure of the basement: nappes, thrust sheets, strike slip structures and normal fault systems. In several areas a number of Alpine and older metamorphic phases can be detected, while other areas are non-metamorphic.On the west, the basement is composed of Palaeo- and Mesozoic crystalline and sedimentary sequences belonging to the Lower to Upper Austroalpine nappe units, and the Penninic unit. In the north, the basement units belong to the Central Western Carpathians nappe system. On the southeast the geological units of the basement belong to the Transdanubian Range unit and subsequently the inner and outer Dinaric related units.

Based on subdivision of Schmid et al. (2008) of the territory we separate 3 main divisions or tectonic Megaunits.

3.1.1.1. Oceanic accretionary nappe system

In the N and NE part of studied area 3 zones are differentiated within this nappe system: the Washberg - Ždánice zone, the Rhenodanubian – Magura flysch and the Pieniny Klippen belt. The Washberg - Ždánice zone mainly consists of Oligocene deep water sediments, and some Upper Jurassic trusted imbricates, Senonian to Eocene marine sediments are also present. The Rhenodanubian – Magura flysch units represent siliciclastic sedimentary complexes. A very deformed and complex unit is the Pienniny Klippen belt, composed of non-metamorphic (Triassic) Jurassic limestones, cherty and marly limestones and Cretaceous–Paleogene flysch sediments.

3.1.1.2. ALCAPA nappe system

The ALCAPA nappe system contains oceanic crust series and Adria derived far travelled nappe systems, overthrusted onto each other predominantly of southeastern vergency. In the deepest positioned, Penninicum or Kőszeg–Rechnitz tectonic window greenshist facies alpine age metamorphic rocks with Jurassic oceanic crust and marly pelitic pelagic sediment protolits (Dunkl & Koller 2001) are exposed.

The Austroalpine and Western Carpathian nappes – a far-travelled crystalline sequences, with multiphase, medium grade amphibolite facies metamorfites and paleozoic-mezozoic cover on them – are overthrusted the Penninic structure zone. The stacked nappe system include the Lower Austroalpine Unit, the Tatricum, the Fatricum and Krizna nappe, the Hronicum and Choc nappe, the Veporicum, the Upper Austroalpine Unit, the Koralpe-Wöltz-Pohorje Unit, the Graz paleozoic and Rába complex, the Ikervár Unit, the Bajuvaric, Tirolic and Juvavic Units, the Greywacke zone Unit, and the Transdanubian Range Unit. The detailed geological description of these units are provided in the summary report of geological models (Maros et al., 2012).,

3.1.1.3. Southern Alps

The Mid-Hungarian Unit represents this Megaunit at the southernmost border of the Supra area. It has very complex buildup, represents strongly sheared and deformed strike slip duplexes of various origin, which consist of Permian to Triassic siliciclastic sediments, marine ramp and platform carbonates.

3.1.2.Paleogene basins

During the Paleogene three major basins of differing tectonic structure and evolution history were formed in the project area as a consequence of the compressional stress-field of the Alpine collision. The Alpine-Carpathian Flysch Belt was formed in the foreland of the nappe fronts behind the Alpine-Carpathian subduction zone. Simultaneously, the Gosau Basins developed due to the rapid uplift in the inner part of the Eastern Alps, in the foreland of the Late Cretaceous nappe fronts. The Hungarian and Slovenian Paleogene Basin are situated in the southern backarc of the Alpine-Carpathian system isolated from the northern foreland.

3.1.2.1. The Flysch basins

The deposits of the Paleogene flysch zone in the studied area appear in the Eastern Alps, the Western Outer Alps, in the Vienna Basin and partly in Slovakia. The formation of the detrital deposits lasted from the Late Cretaceous until the Early and Middle Paleogene, in the Austrian Washberg Zone until the Ottnangian. The sediments are deep water marine, cyclic turbidites, rhythmic coarse sand, conglomerate and sand, as well as fine grained aleurite with marl intercalations (flysch deposits), deep water fans and channel deposits containing conglomerate bodies and shallow marine olistoliths.

3.1.2.2. The Gosau Basins

Its deposits appear in the inner Paleogene basins of the Calcareous Alps and around the Vienna Basin in Austria, in the basement of the Paleogene formations in Slovenia and in the inner, southern part of the Western Carpathians in Slovakia.

In Austria and Slovenia proximal and distal coarse detrital slope fan deposits, channel conglomerates and shelf olistoliths are interbedded in the deep water clay marl and sandy clay marl flysch sequence. In shallow marine environments shallow marine limestone, coral reef and fore-reef sediments are settled. In the terrestrial facies of the Gosau-type sequences in Slovakia bauxite was formed from the Cretaceous up to the Paleocene, which bauxite has the same age as the bauxitic sediments in the Hungarian and Slovenian Paleogene Basin.

3.1.2.3. The Inner Carpathian Paleogene Basin

The Slovenian and Hungarian Paleogene Basins were sheared along the Periadriatic Lineament and have tectonically isolated basin fragments in the strike-slip zones. The sedimentation started at the very end of the Early Eocene and ended at the end of the Late Oligocene. The first paleogene formations overlie Gosau-type deposits in Slovenia and the surface of the Mesozoic in Hungary.

In the coastal, shallow marine environments paralic coal-bearing layers and sandy, clayey lagoon sediments are specific, covered by shallow, then deep water sandy clay marl and clay marl layers. On the carbonate ramps heteropic shallow marine foraminifer-bearing limestone with marl intercalations deposited. In deeper marine environments glauconitic clay marl was formed with interbedded siliciclastic layers. At the end of the Bartonian/beginning of the Priabonian in the SW part of the Paleogene Basin andesite lava and pyroclastic layers are interbedded in the clay marl. At the margin of the rapidly sinking basin, foraminiferal, red algae-bearing carbonate deposition started again, the olistostromes of which appear also in the deep basin sediments. The Eocene succession of the Hungarian Paleogene Basin was eroded by the Early Oligocene denudation. Following the Early Oligocene erosion period deep marine facies characterized the SE-ern part and land and shallow marine environments the NW areas.

In the Slovenian Paleogene Basin during the Early Oligocene andesite tuff, tuffite and marl layers formed. The siliciclastic sedimentation started only at the beginning of the Late Oligocene.

3.1.3.Neogene basins during the Early and Middle Miocene

3.1.3.1. Vienna Basin

The basement of the Neogene-aged pull-apart Vienna Basin is formed by Alpine–Carpathian nappes, and is filled with a more than 5000-m-thick Neogene succession. During the Early Miocene marine sedimentation was restricted to the north, and extended to the south only in the Middle and Late Miocene.

Due to rapid subsidence and sea-level rise, off-shore pelitic sediments were deposited in the northern part of the Vienna Basin, while in the southern part terrestrial and brackish-littoral facies developed during the Karpatian and Ottnangian.

A renewed transgression during the Karpatian–Badenian boundary resulted deposition of predominantly off-shore pelites and locally corallinacean limestone. During the early Badenian deltaic, fluvial and lagoonal sediments and littoral sands and sandy clays formed overlain by neritic off-shore calcareous clays. In the upper Badenian marls, sandy silts were settled, and in the marginal facies sands and conglomerates, breccias, calcareous clays and limestones can be found. The early Sarmatian is represented by silts, calcareous clays deposited in brackish-marine environment.

3.1.3.2. Kisalföld–Danube Basin

The Miocene sedimentation started with the Eggenburgian transgression: littoral gravel and sand covered by offshore sandy clay were dominant. During the Ottnangian and Karpatian terrestrial–fluvial–limnic successions were formed in the basin. Locally thin coal seams and eastward rhyolite tuff interbeddings are known.

The subsidence of the Danube Basin commenced at the end of the Early and the beginning of Middle Miocene. The depocenter of the Kisalföld accumulated off-shore, deep-marine siliciclastic sediments (sandy silt, silt, silty clay marl).

Due to early Badenian tectonic movements two main sedimentary basins existed in the area of the Kisalföld: the Csapod Trough in its western part and the Győr Basin in the east. Badenian successions started with abrasion basal breccia and conglomerate, locally with calcareous matrix. In shallow marine facies it is overlain by corallinacean limestone. The near shore facies are sand-sandstone, the offshore deep-basin facies are represented by fine sandy silt, silty clay marl with sandstone intercalations and sandy-silty claymarl. On the top of the lower Badenian gypsum and dolomite laminae can appear with some tuff intercalations. Along the eastern margin transgressive conglomerates, sandstones and volcanoclastics are overlain by neritic calcareous clays, siltstones and subordinately sandstones. In the NW part calcareous clays and siltstones can be found.

During the upper Badenian calcareous clays, siltstones and sandstones with volcanoclastics and biogenic limestones in the margins were settled in the area.

In the onset of the Sarmatian biogenic calcareous sediments of shoreline and fine-siliciclastic sediments of shallow-marine facies were deposited. The upper Sarmatian is characterised by carbonate successions. In the northern part brackish shallow-water, clay, clay marl, calcareous marl, siltstones and sands are dominant. In nearshore areas conglomerates, sandstones, limestones can be found, locally with lignites and tuffs.

From the Badenian up to the Pannonian trachyte-bearing agglomerate, tuff and marl can be found in boreholes.

3.1.3.3. Styrian Basin

In the western Styrian Basin during the Early Miocene limnic-fluvial deposits developed, in which thick lignite-bearing successions were formed.

During the Karpatian several hundred-meter thick off-shore succession was deposited. Marine facies (limnic-deltaic deposits and fine-clastic sediments) developed at the transition to the western Styrian Basin. Acidic to intermediate volcanism took place until the end of the early Badenian (Handler et al. 2006) too. At the end of the Karpatian erosion occurred, followed by the deposition of some terrestrial breccia, conglomerate, red clay and debris.

In the early Badenian the volcanic activity continued and the marine deposits have a large areal extent: pelitic sedimentation was predominant, but in some places fan-deltas developed with thick conglomerates, carbonates interfinger with shallow-marine siliciclastic or coarse-clastic deltaic formations and Corallinacean algae patch-reefs were formed around basement highs. In the West Styrian Basin lagoonal deposits are predominant. At the Badenian–Sarmatian boundary erosion and progradation of fluvial and deltaic systems happened.

During the Sarmatian marls were deposited in large areas and on the topographic highs bryozoan-serpulid biostromes are specific. At the top of the Lower Sarmatian erosion took place and the Upper Sarmatian silts, sands, ooliths, marly limestones were subsided due to the oscillating sea level (Gross et al. 2007).

3.1.3.4. Zala Basin

The Lower Miocene is represented by the coarse-grained fluvial, and fine-grained lacustrine sediments. The continental deposits of the western part of the Zala area pass up to the Karpatian, overlie the Mesozoic basement and are overlain by the Badenian formations. Some boreholes penetrated volcanics (‘lower rhyolite tuff’).

The Karpatian coarse-grained facies is predominant only along a narrow strip at the marginal zone; the internal part of the sedimentary basin is characterized by thick pelitic successions. Regression at the end of the Karpatian and in the lower Badenian resulted in the appearance of coal-bearing marsh facies and clastic deposits. The whole area of South Transdanubia may have been a shallow archipelago.

In the area the Badenian sediments predominantly overlie the eroded surface of the Palaeozoic, Mesozoic and Eocene formations. In the early Badenian the nearshore areas were characterised by a marine coarse-clastic to sand–sandstone succession with lateral transition into the biogenic limestones. In restricted or semi-restricted bays, coal-bearing successions were formed. In the northwestern basinal area the sedimentation was continuous: marls and silty marls were settled.

Sarmatian basically has a regressive character, but locally it shows transgressive features. In the NW part of the basin and in the eastern margin it shows continuous transition from the Badenian and regressive characteristics, in the centre of the basin it is predominated by sandy beds. At this time the deepest part of the basin coarse-grained sandstone was formed, locally with small-sized pebbles. Southwards, clastic sediments become finer; pelites and silts are predominant. In the marginal areas the Sarmatian beds decrease and become more marly. Coarse-clastic, biogenic limestone facies of the Sarmatian can be found in areas which were in the highest position during the Badenian. At the end of the Sarmatian brackish-water sediments were deposited.

3.1.3.5. Mura-Dráva Basin

A granodiorite rock body of Early Miocene age can be traced in the Slovenian area. The sedimentary infill of the “core complex” stage lasted from the Late Ottnangian to the Karpatian as a part of the first synrift phase (Jelen & Rifelj, 2005). The initial infill onto the Pre-Cenozoic basement are represented by sandstone, conglomerate, muddy breccia and conglomerate and sandstone, sand, sandy marl Tuffs also dated to the Early Badenian age are.

The Mura–Zala Basin was a turbiditic basin with about 1300 thick sediments until the Early Pontian (Jelen & Rifelj 2001, 2003). In the central part of the Mura–Zala Basin, on the Murska Sobota block the deposits are missing.

At the Karpatian/Badenian boundary erosional unconformity caharacterizes the shallow parts, and coarse grained fans deposited in the deeper parts of the sub-basins. In the deepest parts of the basins a “starving basin” condition evolved. The Lower Badenian sedimentary rocks onlap also onto the Pre-Tertiary (Pre-Paleogene) basement: deep water conditions evolved over the algal limestones and fans, mud rich turbidites and hemipelagic mud began to fill up the lowest parts of the basins. In the Upper Badenian sand rich turbidites are proximally prevailing, while in the distal parts progradation took place.

The Early Sarmatian is represented by heterolitic siliciclastic sediments and carbonates deposited in the shallow parts, while turbiditic sedimentation persisted in the deeper parts.

3.1.4.The Neogene basins during the Pannonian

The Pannonian (Late Miocene and Pliocene) geohistory is characterized by the presence of Lake Pannon. This “Lake” got isolated from Paratethys and was infilled by sediments of large tickness: the shelf-slope system prograded chiefly from NW to SE. During the Lower Pannonian coarse sediments – abrasional conglomerates – were deposited along the shorelines. Fluvial deltas were formed along the feet of mountain ranges. The most prevalent deposits of this time were the pelagic marls of the 'starving' basin. The first infilled basin was the Vienna Basin, so deltaic than alluvial units were formed. As the shelf-slope system started to prograde turbidites started to deposit. On the slope silt was deposited, coarser sediments settled only in turbidites.

During the earliest Upper Pannonian delta front sediments accumulated on the sedimentary shelf were formed. In the central regions of the basin the sedimentation resulted in wide and thick sheets of sand with relatively good connectivity. After that a deltaic plain, than an alluvial plain was formed with large amount of floodplain silt and mud, and isolated channel sand bodies.

During the Early Pliocene, features of the fluvial systems have been changed: the rivers deposited thick beds of gravel close to the margins and also in the Danube Basin, while variegated clay was formed in some of the central areas. The Upper Miocene-Pliocene basalts and their tuffs in the area are related to the crustal thinning of the Pannonian Basin.

3.2. Regional groundwater flow systems

The groundwater flow system of the Supra-Regional area is controlled by the considerable hydraulic potential between the recharge and discharge areas (i.e. surrounding mountain chains and low-lying basin), sufficient recharge (precipitation) and extensive deep-lying permeable formations outrcropping on the surface on large areas. These basic conditions are provided by the geological buildup of the basin. At the project area the mountain regions represent the groundwater dives and natural boundaries of the flow system. These regions having higher relief (Alps, Male Karpaty, Carpathians, Transdanubian Midmountains) serve as the main recharge areas, where the basement rocks crystalline, or carbonate) outcrop. Part of the infiltrated precipitation returns to the surface in the form of cold water springs at the basin margins, or within the mountain area after a short path forming local simple gravity-driven flow systems.

The other part is infiltrating toward the deeper layers and enters the regional flow system. At bigger depths, along the deeper flowpaths the groundwater warms up, and changes its chemical character due to water-rock interactions. Where the fault zones have high vertical permeability and are of a large vertical extent they may form so called “geothermal heat chimneys” (open convection cells).

The regional flow systems either terminate at springs at the margins of the mountain regions, or continue in the depth below lowlands, in the deep sinking basement units. In some places where the basement is connected to the porous sediment formations filling the Neogene basins, the groundwater of the basement aquifers pass over to the porous layers, forming the flow system of the sedimentary basins. In these cases thermal groundwater also feeds the overlying shallow subsurface freshwater Quaternary and Plio-Quaternary aquifers. Otherwise the flow system of the basement is separated from the above described flow system of the porous aquifers, and the main discharges of the basement system are only the springs at the margins of the mountains.

The other major type of the basement reservoirs include those deep carbonate rock bodies with fairly stagnant thermal groundwater reserves that do not have direct hydraulic connection (supply) with the surface karst systems. They normally contain thermal groundwater with higher temperature and higher salinity with rather NaCl type (fossil waters) and may have a restricted recharge from the overlying porous aquifers. When the geometry (vertical or subvertical permeable zone of the closed basement aquifers, i.e. conduit channels along larger fault zones) makes it possible, a closed thermal convection (free convection) may develop.

The Middle Miocene aquifers (abrasional and shore sands, gravels, reef carbonates, etc.) directly overlying the basement rocks form a joint hydraulic unit with them.

The groundwater flow system of the Neogene sub-basins is divided to an upper gravitational part and a deeper part, where the density and heat difference driven flow is added to the gravitational system.

On areas far away from the gravitational flow systems stagnant or very slow flows operate. These groundwaters generally originate from the sea-water of the last transgression of the geological evolution of the area, i.e. they are fossil confined groundwaters. In the basin areas the presence of the former or recent overpressured zones has to be taken into consideration. These are generally formed on areas where thick clays and clayey marls are present (‘Miocene’-‘Pannonian’ clayey marls); mainly compactional and/or tectonic, diagenetic processes may take part in their formation. The slow fluid migration by cross-flows from the overpressured zones towards the basement, or to the upper aquifers is important from the hydrogeochemical point of view. The amount of water deriving from these units is generally much smaller than the water budget of the main aquifers, but the high dissolved solids content of the overpressured zone’s water significantly contributes to the hydrogeochemical character of the exploited thermal waters and often determines their balneological/medicinal value.

The regional groundwater flows collect heat from a large subsurface area, then uprise towards the springs, a much smaller area compared to the territory of the »heat-recharge«. The gravitational flow systems of the porous aquifers in basin areas can be divided into regional, intermediate and local systems.

The deepest regional flow system penetrates till the delta-front and the delta-plain sands of the Upper Pannonian sedimentary sequence. The sedimentary and post-depositional erosion processes may significantly modify the stratification of these units, and as a result the forced flow paths and recharge/discharge conditions, too. Under favourable conditions the sandy aquifer units are outcropping, or are in direct contact with Quaternary aquifers on the hilly areas with a higher hydraulic potential, therefore providing a fairly quick and direct recharge. The system is characterized by a strong anisotropy (Kh/Kv often higher than 5000) at a larger, regional scale due to frequent alternation of the sand-silt-clay layers. Although the permeability of the clayey-marly layers is 1-2 magnitude lower than that of the sands, this is still enough to provide hydraulic connection between the sand layers, thus make the entire sedimentary succession one hydrostratigraphic unit.

The intermediate flow systems encompass the multi-level sandy aquifers of the Upper Pannonian delta-plain sedimentary sequence. They also play a role in the recharge of the porous and karstified/fractured basement geothermal aquifers. The shallowest groundwater (local) flow system can be divided into two main types. On the hilly areas the precipitation percolating through the pre-Quaternary weathered, or coarse- grained sediments feeds the Quaternary (mostly Holocene) alluvium of the valleys. Here this local flow often meets the intermediate and regional flow systems. The larger streams and deeper and larger alluvial aquifers form the other type, which is a discharge of the deeper flow systems.

In the Transenergy supra-regional area we can distinguish the following regional flow systems related to the major geological units:

- Vienna Basin,
- Styrian Basin,
- Danube Basin and Kisalföld sub-basins,
- Mura Basin,
- The main karst system of Transdanubian Midmountains and its continuation in the basement,

The relations between these flow systems are not unambiguous in each case.

3.2.1. Vienna Basin

The Vienna Basin is a fault-bounded graben or a pull-apart basin respectively, which is situated in the transition area between the Alps and the Carpathians.

From groundwater and especially from thermal water point of view, the Mesozoic calcalpine units are the most important, where limestones and dolomites are predominate. Joints and fissures with high conductivity are very common within these rocks. The Triassic dolomite (the so called "Hauptdolomite”) has a porosity range of 5-13%, permeability varying between 10^{-8}–10^{-5} m/s, but the whole formation can be characterised with a conservative mean value of about 2.5 10^{-6} m/s. Aquifers for geothermal use lie in the pre-Tertiary basin, whereas in the unit of the Calcareous Alps thermal waters (with temperatures >100 °C in some places) can be expected.

The maximum thickness of the Neogene is considered to be 5500 m in the Schwechat depression. Most of these Neogene sediment layers are aquitards, but there are some layers in the basin filling aquifer systems which are favorable for geothermal energy exploitation (for example Aderklaa Conglomerate).

The uppermost Pannonian and Quaternary formations have several aquifer layers, but they take part only in the shallower, cold water flow system.

In the Viennna basin two different types of thermal water systems can be separated (Wessely 1983). The entire hydrodynamic system recharges from permeable rocks in the Eastern Alps and the Central Alps (Leitha Mountains) as well as from the Carpathians. Groundwater is flowing in the deeper layers to the direction of the basin. In the basin the "Leopoldsdorf Fault System blocks the flow, so the groundwater turns back to the direction of the mountains, and discharge in springs along the margin the Southern Vienna Basin (actively recharged hydrodynamic systems with low to moderate TDS content). The other type is characterized by Two different types of thermal water systems can be separated (Wessely 1983), the partially overpressured brines with mainly stagnant groundwater and the actively recharged hydrodynamic system with low to moderate TDS content. The thermal aquifers of the central depression zone of the Vienna Basin (including the north-eastern margin in Slovakia) are not connected to active recharge systems and can be described as connate brines (NaCl content > 20g/l). While the brine-type aquifers are widely spread across the entire Vienna Basin and can be found both in the permeable Neogene sediments and in the basement reservoirs of the central depressions, the low TDS thermal waters with direct recharge are found in the high plateaus at the margins of the Southern Vienna Basin. The 2 systems are separated by a major fault system, the so called "Leopoldsdorf Fault System".

At present major utilizations of thermal water are located at the margins of the Southern Vienna Basin (eg. Baden, Bad Vöslau, Bad Fischau, Berndorf). More than 3000 wells exist in the Vienna Basin due to intensive hydrocarbon exploration and exploitation.

The flow system of the Austrian part of the Vienna Basin are shown in Figure 16 and Figure 7.

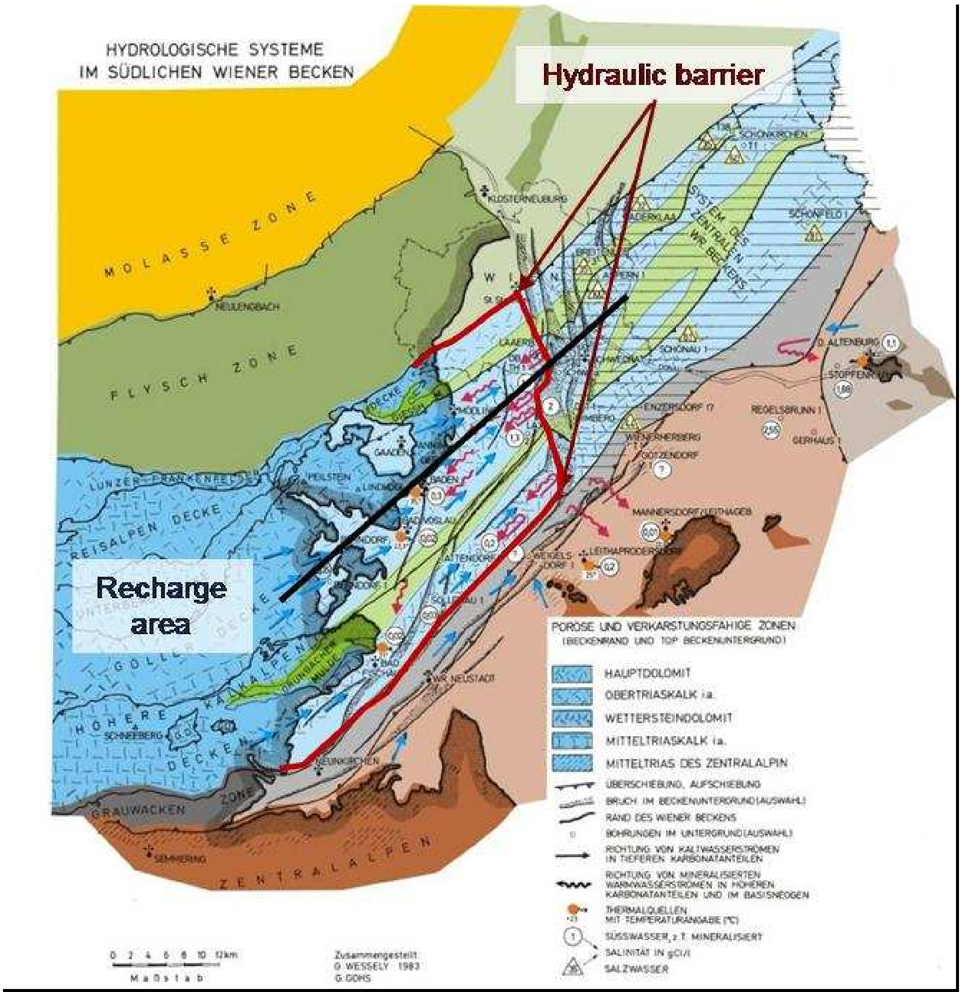

Figure 6. Hydrogeological sketch of the Vienna Basin (after Wessely 1983). Note the blue and red arrows. Former represents the cold, later represents hot basin karst water flow paths.

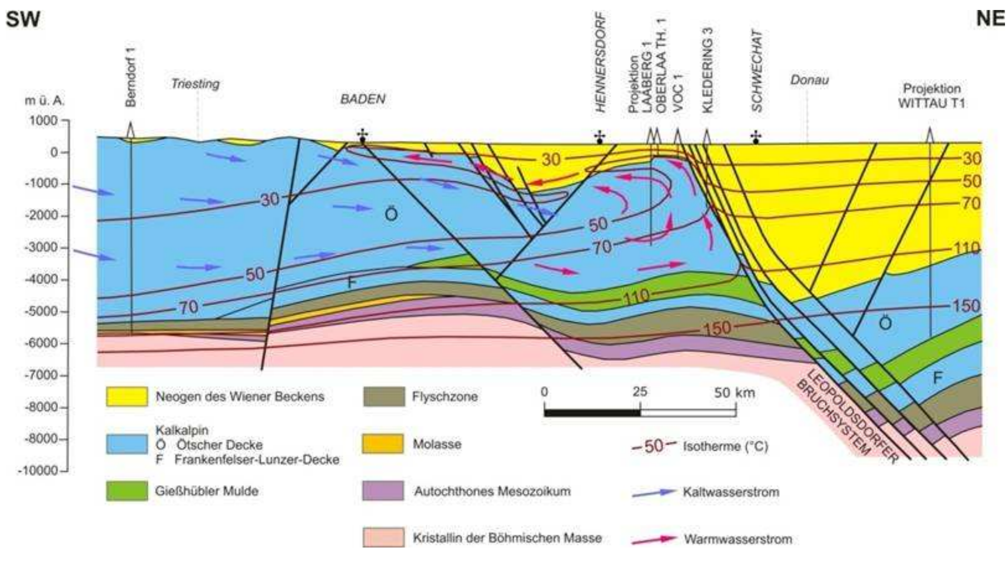

Figure 7. Hydrogeological cross-section along the Vienna Basin (after Wessely 1983)

In the north-eastern Slovak part of the Vienna Basin, four geothermal structures (Laksar elevation, Sastin elevation, Zavod-Studienka sunk belt, Lab-Malacky elevation) with different TDS content were identified. These thermal waters are also found in the Triassic carbonates and in the overlying Neogene (Eggenburgian) sediments, and form one single hydrogeological system. Their temperatures range between 40-140ºC. Although the TDS content varies between 5-130 mg/l, all of them are Na-Cl chemical types. Thermal groundwaters with the lowest TDS content can be found in the Laksar elevation with TDS values between 5-7 g/l. It has an open structure with infiltration, accumulation and spring area. Sastin elevation represents a semi-open structure, where the spring area is missing. The thermal waters in the Sastin elevation have a TDS content between 7-15 g/l. Zavod-Studienka sunken belt and Lab-Malacky elevation are closed structures. The Závod-Studienka sunken belt has thermal waters with 15-25 g/l, while very high TDS content brine waters can be found in the Láb-Malacky elevation (Figure 8 and Figure 9).

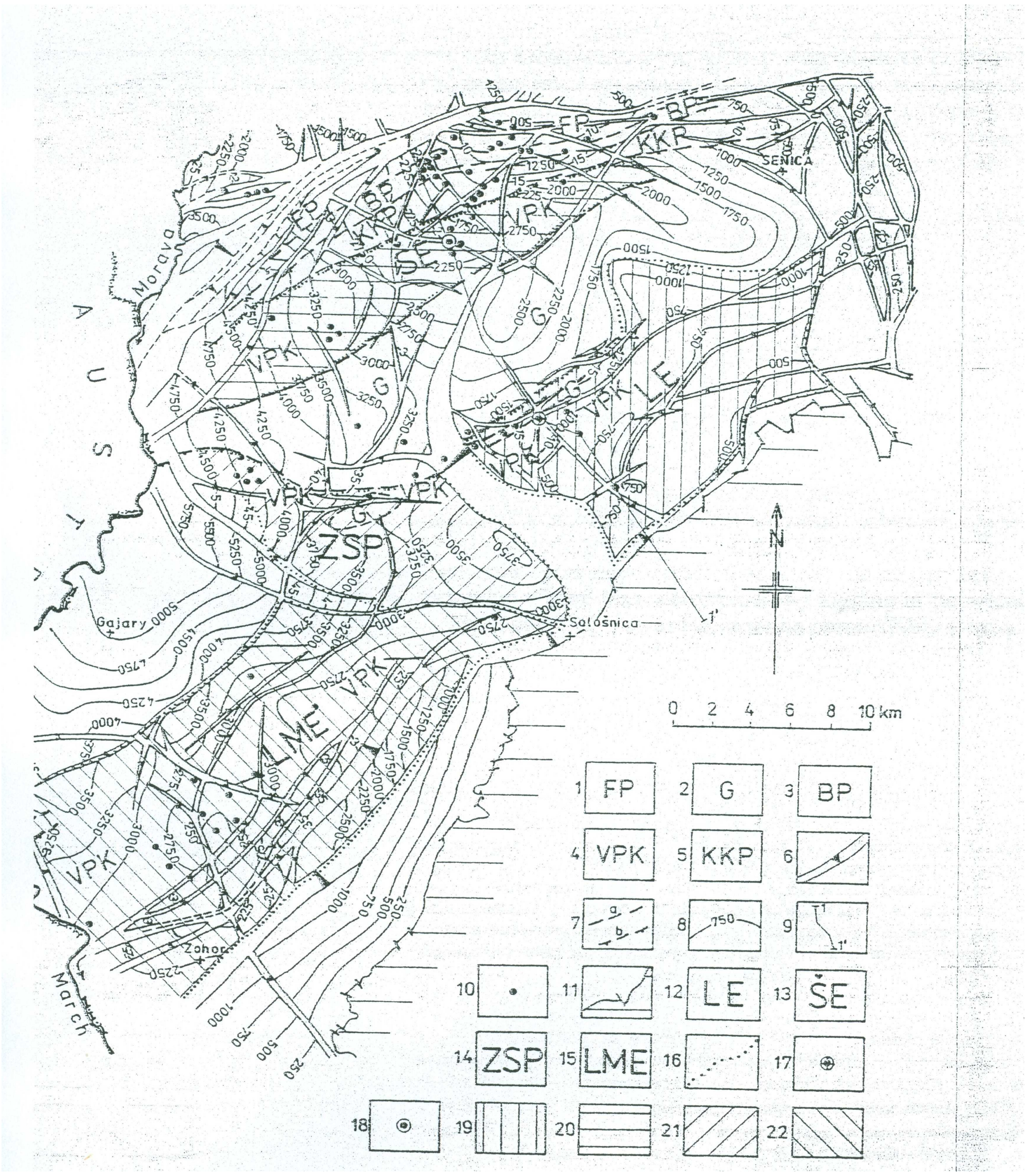

Figure 8: Hydrogeological flow system in the Slovakian part of the Vienna Basin (Remsik et al. 1989)

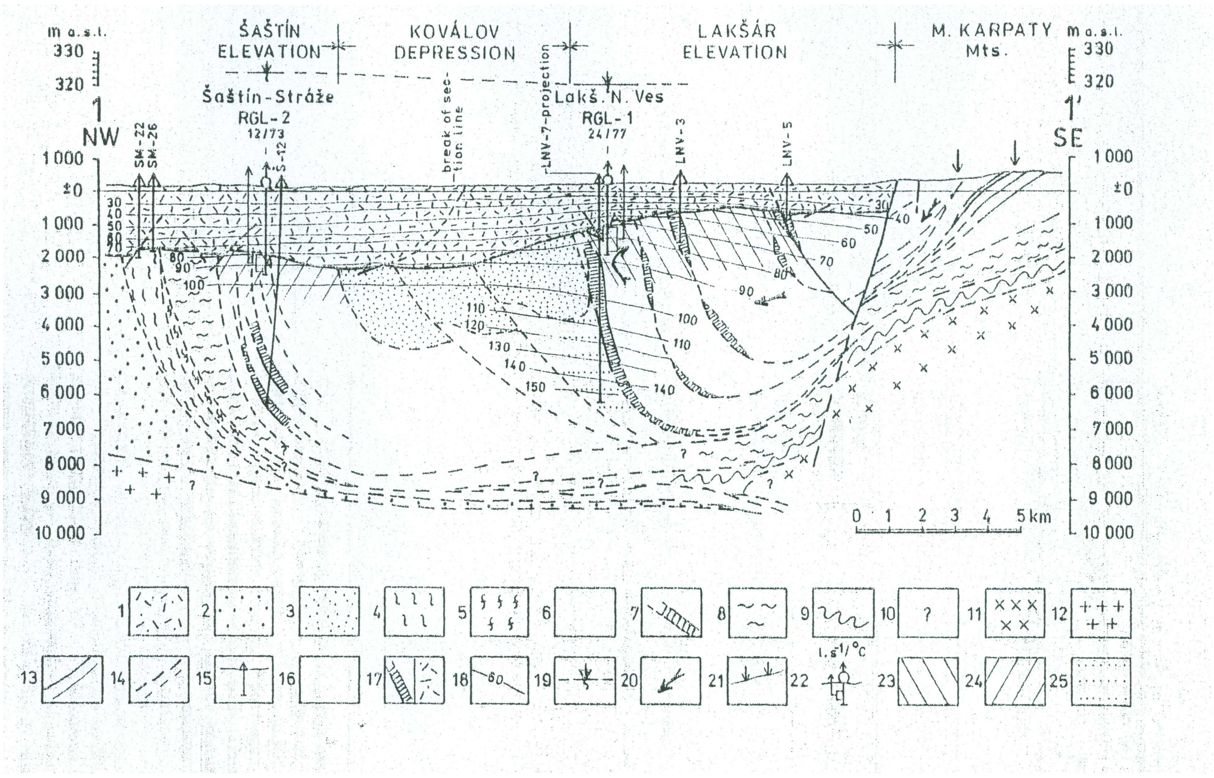

Figure 9: Hydrogeological cross-section along Slovakian part of the the Vienna Basin (Remsik et al. 1989)

3.2.2.Styrian Basin

Due to the enhanced heat flow, the Styrian Basin is the second most important geothermal region in Austria. The Styrian Basin is built up by Neogene formations. Sediments of Karpatian to Upper Miocene age with a maximum thickness of 2900 m have been deposited. Thermal aquifers can be found in the pre-Neogene basement. It is represented by Austro-Alpine basement rocks, in some parts of the basin rocks of the Palaeozoic of Graz, which belong to a higher nappe, overlying the crystalline basement. The upper part of the Palaeozoic is formed by dolomites of Devonian age. Due to intense tectonic deformation, the dolomites are highly fractured and therefore have good aquifer properties with favourable permeabilities. In the existing boreholes, dolomites of different lithotypes are present. According to the deuterium and oxygen-18 stable isotopes, the origin of the deep groundwater of Waltersdorf is entirely meteoric, but the water of Blumau and Ilz is not. It shows that the Palaeozoic basin floor has been flushed through by meteoric waters, but intensive hydrodinamic flow alters with stagnant water of non-meteoric origin, forming different subsystems without connections.

The entire section of the Tertiary basin filling comprises clastic sediments of Badenian to Pannonian age. Aquifers bearing thermal waters are in the Badenian and Sarmatian sequence, while the other Neogene sediments have got an aquitard character. The Badenian and Sarmatian aquifers consist mainly of sand and sandstones with different clay and silt contents. The transmissivities of the Miocene aquifers are one to two orders of magnitude lower than those in the Palaeozoic carbonate rocks. The Miocene volcanism and post volcanic activity cause CO_2 anomaly (Figure 10).

The waters from the perforated horizons in the Upper Badenian have nearly double of mineralization. Free CO_2 or CO_2 gas is also not present in this horizon. In the Fürstenfeld subbasin, where the borehole of Fürstenfeld has tapped formation waters in the Middle Badenian (Sandschaler Zone) the water has a total dissolved solid content of 45 g/l (Na-Cl type).

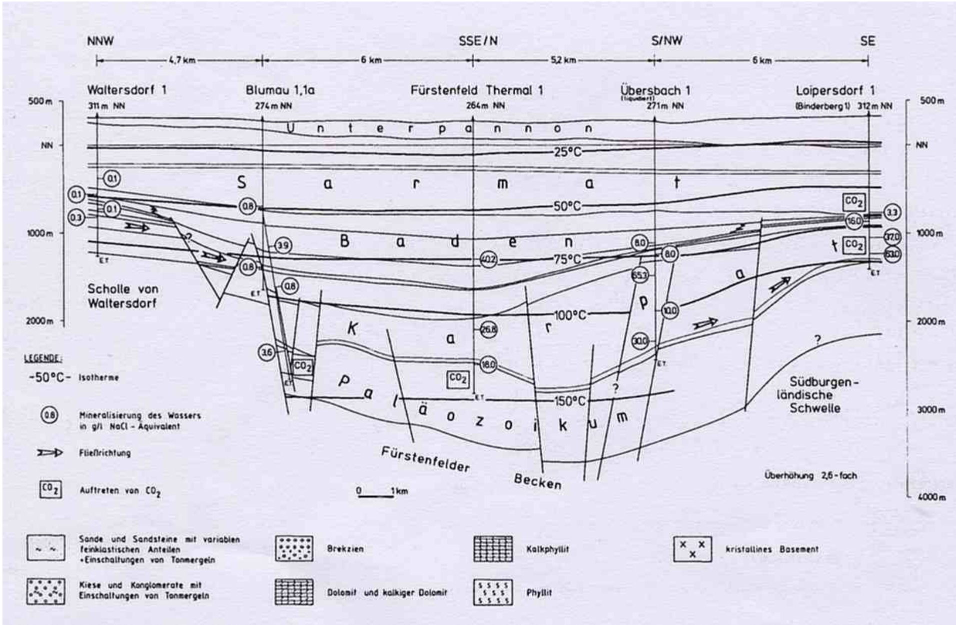

Figure 10: Cross-section in the Styrian Basin (Zötl and Goldbrunner 1993)

Drinking water supplies are from wells in the Neogene sediments at a depth of up to 300 meters. More than 1,500 private wells have been encountered, but there are also public water supplies.

3.2.3. Mura-Zala Basin

The Mura-Zala Basin is situated at the western foreland of the Transdanubian Midmountains. In the N-ern part of the basin, mainly in Austria, the pre-Neogene basement consists of the formations of the Upper Austroalpine, Wölz-Koralpe-Pohorje nappe, Graz Palaeozoic, and Mesozoic cover sediments of the Southern Alps. The Neogene sediments finger into Slovenia like gulfs, their thickness can reach 4500 m.

The main geothermal aquifers are in the Mura, Lendava and Špilje&Haloze formations (Pannonian). The Mesozoic carbonates and Paleozoic metamorphic rocks probably do not take an important part in the regional flow system, but contain mostly stagnant groundwater with minor recharge, which is limited to the fault zones (Lapanje, 2007). The metamorphic and crystalline basement rocks are not forming aquifers. They are considered as fractured formations with lower permeability.

In the northwestern part of the region, the carbonate Mesozoic aquifer is positioned in the narrow and deep Radgona –Vas tectonic half-trench south of the Burgerland swell. The Radgona – Vas tectonic half-trench was developed along the Rába fault system in a SWS – ENE direction. Although the main aquifer is built up of the same geological formations in the whole Transdanubial Mountain Range, the hydrogeochemical composition of this aquifer at the transboundary region differs significantly. In the Western part of the zone we can find salty waters with high TDS content, while in the Eastern part of the Mesozoic basement aquifer the TDS contents are much lower.

According to available data, the thermal water from Preneogene rocks is extracted only in Bad Radkersburg (Rad-1 and Rad-2) and Benedikt (Be-2/04). In Bad-Radkersburg Mesozoic, while in Benedikt Paleozoic metamorphic formations are the host rocks.

General groundwater composition is shown in a Piper diagram (Figure 11). Except one mixed Miocene sample, the available data show a general chemical evolution trend along the flow paths, from Ca-Mg-HCO3 type to Na-Ca-HCO3 type in the Neogene aquifers, and Na-HCO3, Na-HCO3-Cl type in the carboniferous basement.

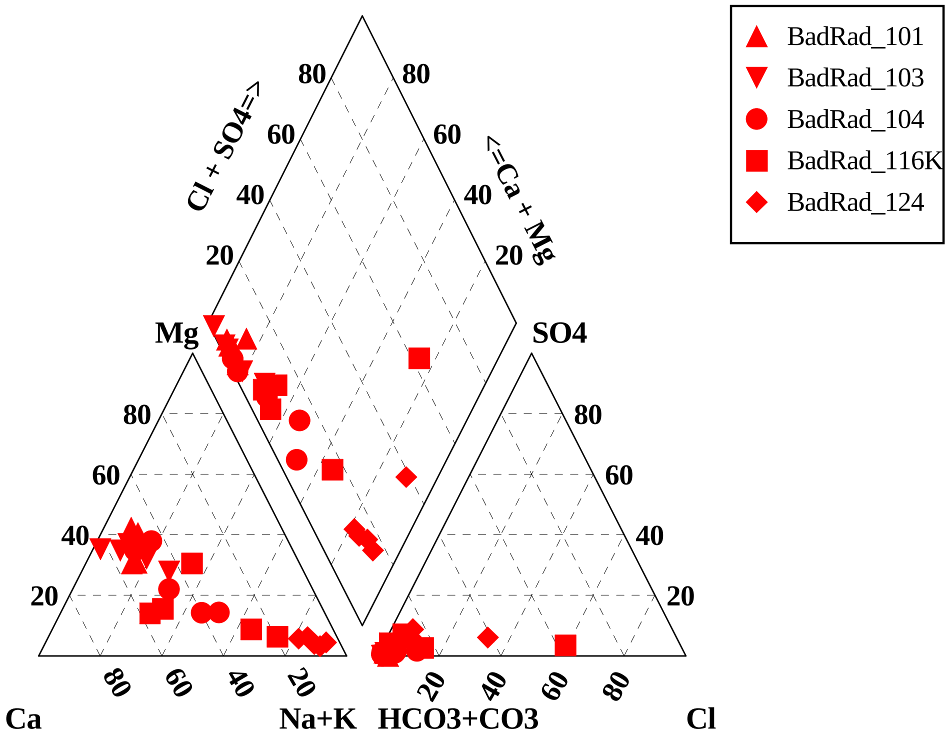

Figure 11: General groundwater composition as shown in a Piper diagram, for selected units of Bad Radkersburg area of the Mura-Zala Basin

Legend: 101 – Quaternary; 103 – Upper Pannonian (cold and lukewarm waters); 104 – Upper Pannonian (thermal waters); 116K – mixed, Miocene (sometimes with Upper Pannonian); 124 – Mesozoic (in general)

The older Miocene aquifers (abrasional and shore sands, gravels, reef carbonates, etc.) directly overlying the basement rocks form a joint hydraulic unit with them. Delineation and selection of the potential basement geothermal reservoirs should consider the areal extent and thickness of these Miocene rocks (especially Badenian and Sarmatian aquifers), as well as their hydrogeological parameters. We do not have enough information on the hydrogeological and hydrodynamic role of those Lower Miocene coarse-grained porous sediments of the deep basins that are not connected directly to the basement aquifers and that of the Miocene and Pliocene vulcanites.

Different well-tests of hydrocarbon exploration wells, measured pressure fields, hydrogeochemical characters also suggested that the older Miocene aquifers which form a joint hydrodynamic system with the basement reservoirs have an outstanding importance in the Zala basin.

The older Miocene aquifers are covered with thick Miocene aquitard layers, which separate them from the deep regional flow system of the porous aquifer system.

In the central part of the Mura-Zala basin faults often act as barriers as they cut, move and isolate water-bearing layers between each other (Radenci, Petišovci and Dankovci). Due to the higher horizontal than vertical permeability in the porous flow system the flow direction parallel to the stratification is enhanced. The high pressure in the central part of the basin is assumed to result in the thermal water flow towards the basin margins (Pezdič, 1991).

The higher salt content of the Badenian Sea transgression is flushed out by the less mineralized "fresh" groundwater from both the karst and porous sediments, and also from the fractured aquifers in some Paleozoic metamorphic and Mesozoic carbonate rocks. The precipitation infiltrated through the coral-reefs and basal-conglomerates of the Badenian-Sarmatian time, and was preserved only in those zones where neither the young groundwater, recharged through continuous precipitation infiltration, nor the Pannonian Lake with its slightly higher density did not flush it out.

Shallowest regional groundwater flow occurs in the upper, active aquifer system in the Quaternary, Plio-Quaternary, Pliocene and Pontian sediments and rocks. Natural outflow from the unconfined Quaternary and Plio-Quaternary aquifers is limited to the surface water flows (rivers, lakes) but evapotranspiration also affects them. Springs occur at the bottom of the valleys.

The main conclusion (Rman and Szőcs 2011) of the research carried out in the T-JAM project is that transboundary geothermal aquifers between Slovenia and Hungary do exist.

Hydrogeochemistry has confirmed (Szőcs et al. 2012) that a regional groundwater flow is hydrogeologically realistic in some aquifers in the Mura-Zala Basin. Groundwater is of meteoric origin. A strong water-rock or water-rock-gas interaction, between groundwater and carbonates and/or CO2, is evident locally. In case of strong water-rock(-gas) interaction a significant shift in Carbon-13 towards very positive values means they cannot be used for radiocarbon age corrections, since the original DIC values have been greatly altered.

The Ptuj-Grad (SLO), Zagyva and Somló-Tihany (HU) Formations probably form an active regional groundwater flow system, fed by recharge from the northern Goričko hills in Slovenia. This recent to a few thousand years old water has a flow direction from NE Slovenia to SW Hungary. This groundwater has a low TDS content (mostly around 200 mg/l) and a high (Ca2++Mg2+)/(Na++K+) cation ratio. Nitrogen is present in the Zagyva and Somló-Tihany Formations, while the main dissolved gas in the Ptuj-Grad Formation groundwater is CO_2.

The Mura (SLO) and Újfalu (HU) Formations are a part of the active regional thermal groundwater flow system. This groundwater has higher TDS values (up to 2000 mg/l), but lower (Ca2++Mg2+)/(Na++K+) cation ratio compared to the previous group. This flow system is probably hydraulically separated from the shallower one. Water might have infiltrated during the Pleistocene, probably in the last interglacial. Mostly air is dissolved in the groundwater, but locally it is enriched in CO_2 or methane. Samples show strong diffusive subsurface degassing and some of them indicate the presence of mantle derived helium.

The Lendava (SLO) and Szolnok (HU) Formations contain groundwater which is probably not part of the active regional groundwater flow system. Water infiltrated in the same period as the previous group, but is now more or less stagnant and isolated from its surroundings, resulting in high TDS content up to 15000 mg/l.

A transboundary flow is less likely in the Middle Miocene Formations aquifers since they are of a limited extent or isolated from their surrounding. They have a high TDS content, above 10 g/l (Figure 12).

One conclusion of the T-JAM project is that Mesozoic aquifers investigated in Hungary and Slovenia are not comparable.

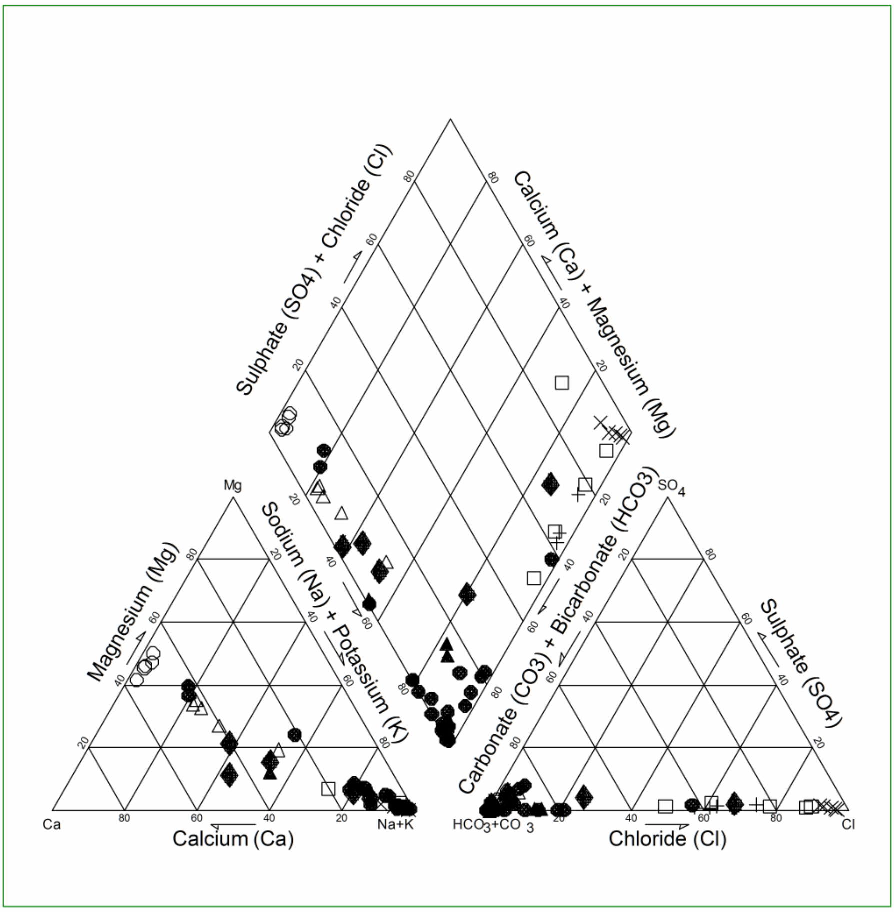

Figure 12: General groundwater composition as shown in a Piper diagram, for selected units of the Mura-Zala Basin

Symbols: filled circle – new samples, open circle – Quaternary, open triangles – Somló-Tihany, Zagyva Formation, filled triangle – Újfalu-Mura Formation, plus – Szolnok-Lendava Formation, filled diamond – Haloze-Špilje Formation, x – Lower Pannonian, Sarmatian, Badenian, Karpatian Formations, open square – Lajta limestone

3.2.4.Danube Basin and Kisalföld Neogen sub-basins

The geological boundaries are the Malé Karpaty Mts., the Leitha Mts., the Sopron Mts. in the WNW, the Transdanubian Midmountains in the SE, and the basinal infill truncations at the E–NE. In the north it is fringed by foot hills of Považský Inovec Štiavnické vrchy and Krupinská vrchovina. Toward southwest the basin continues below the Kisalföld Plain into the Mura-Zala Basin.

As for the period of the Neogene basin evolution, the region falls in the area of the Kisalföld Basin in Hungary, and the Danube Basin s. l. The basement is made up of two different complexes of two different geological histories. The basement of the area at NW of the Rába river (Rába tectonic line) is made up of metamorphic rocks and represent the extensions of the East Alpine nappe units towards Hungary. Southeast of the Rába Line the basement is built up of Palaeozoic and Mesozoic rocks of the Transdanubian Midmountains. The Transdanubian Unit will be discussed in details Chapter 3.2.5.

The Alpine crystalline basement crops to the surface in the Leitha and Sopron Mountains. Tatric unit shows similarities, and is regarded to be a Carpathian continuation of the Central Alpine units in Slovak territory. In the Malé Karpaty Mts. the Tatric unit system is represented by crystalline rocks and cover sequences (Late Permian to Cretaceous), restricted mainly near to the western margin of the mountain ridge, so it does not affect directly the Danube Basin region. The Hainburg Hills are also regarded to be a part of the Carpthian Malé Karpaty Mts. (Császár et al. 1998).

The Upper Austroalpine nappes are located between the Rába and Répce Lines in a strip about 30 km wide. In our regional area a Silurian metavolcanite, a questionable Devonian phyllite and a Devonian dolomite formation are known. The knowledge of the whole complex (Rába Complex) is little because of the few borehole data.

Due to early Badenian tectonic movements two main sedimentary sub-basins existed in the area of the Kisalföld: the Csapod Trough in its western part and the Győr Basin (the so called Danube Basin) in the east. These two depressions were divided by the Mihályi Ridge.

The crystalline basement has no significant influence on the groundwater flow system. They have fissure-type permeability. They differ in stratigraphy, but the main features are the same. Usually they can be characterized by intensive heterogenity, decreasing fissure aperture closing downwards causing the decreasing of permeability, and improved hydraulic conductivity due to tectonic effects.

Except for the Mesozoic aquifer system of the Danube Range, only some smaller blocks of carboniferous basement aquifers appears.

The Levice block is located in the northeastern part of Danube Basin. It is composed of Mesozoic rocks of the higher nappes, locally underlain by the remnants of the Mesozoic envelope of the crystalline complex (Fusan et al. 1979). This Mesozoic plateau dips first smoothly and then more steeply westwards. It has only westward continuation. The aquifer is formed by mainly Triassic dolomites together with the basal Badenian clastics. The temperature of the water is 69-80 °C, and its mineralization reaches around 19 g/l.

The representative block of Graz Palaeozoicum (part of the Upper Austroalpine nappes) in the Bük-Sárvár region shows an other type of the carboniferous basement aquifers. Although the known spatial extent of the aquifer formed by Devonian dolomite is not too big, the hydrogeological character is not uniform. Conductive areas can be found only related to wider open fractures, they are most often located along the elevated blocks of the dolomite basement. Two separated fractured flow systems were explored by boreholes. The reservoir of Rábasömjén together with the directly covering Miocene aquifers (limestone and sandstone strata) form a significant closed system. The reservoir of Bük is separated from the reservoir of Rábasömjén at northwest along tectonic zones. It is supposed that the Bük reservoir has got its recharge area in the foreground of the Wechsel Mts.

The Dubnic depression is a special type of basement aquifers. It is filled mainly with Miocene sediments underlain by crystalline shists and granitoids of the Veporicum. The aquifer is built u pof basal Badenian clastics (conglomerates, sandstone) at a depth between 1000-2000 meters. It represents a closed reservoir, with temperature of 52-75 °C, and mineralization ranges from 10-30 g/l.

The Danube Basin and the Neogene sub-basins of Kisalföld are filled with several thousand meters thick porous sediments.

The northern part of the territory is situated in the dish-like shaped Danube Basin. The more than 6000 meter deep basin has brachysynclinal structure. The older layers which outcrop at the edge of the basin can be found at gradually deeper positions toward the centre of the basin. The older Miocene and Pannonian complex are composed mostly of unconsolidated strata of gravels, sands and clays. These are locally cemented by calcium carbonate to form conglomerates, calcareus sandstones, or organogenic limestones. The covering Quaternary layers are represented by gravels and sands. The maximum thickness (520-600 meters) occurs in the region of Gabcikovo and Baka.

The Miocene aquifers are connected in each case to the basement aquifers, especially to the basement highs and form a single flow system. They are represented by Badenian or Sarmatian sands and limestones. They content fossil waters with high salinity.

The Upper Miocene low permeable and thick marl and clay sequences together with the Lower Pannonian layers act as regional aquicludes. They separate the flow system of the basement from the deep (usually thermal water) flow system of the porous formations of the Pannonian reservoir.

The lower part of the Upper Pannonian formations can be characterized by interlayer leakage, intergranular permeability and confined groundwater level. It contains thermal waters of 42–92 °C linked to mainly sands and sandstones aquifers. The aquifer layers of the central part outcrop at the edges of the depression. Towards the interior part of the basin, the number of the sandstone aquifer layers increases, but simultaneously thickness, porosity and permeability decrease as a result of sediment compaction within the young sedimentary basin. Commonly, the up to 10 meters thick sand bodies are lens-shaped and cannot be followed laterally for long distances. The sandy aquifer layers vary with aquitard clay, sandy clay layers. The vertical and lateral extent of the aquifer layers are varying quickly.

Quaternary alluvial sediments form a common unconfined reservoir which is in hydraulic connection with the regional thermal water flow system. The groundwater regime depends on the discharge from the Danube, at Gabcikovo region it can be as deep as 30 meters. Below this limit the influence of deep regime becomes evident with all its hydrodynamic features.

The Quaternary alluvial aquifers have special hydrogeological importance. The thick gravel and sand layers store a great amount of good quality water with a great potential for the future drinking water resources. The dynamic discharge in some places exceeds 8 m^3/sec.

With respect to lithology, the porous Pannonian aquifers and overlying beds have been divided into six hydrogeological units. Each represents a complex with different ratio of aquifers and aquicludes. The waters in the Central depression are either marinogenic or petrogenic and are divided into five chemical types (Franco et al. 1995).

The very slow flow rates in the upper part of the Neogene sedimentary succession are supported by the very negative δ18O-δD values. Figure 13 shows the general groundwater composition of the Danube Basin.

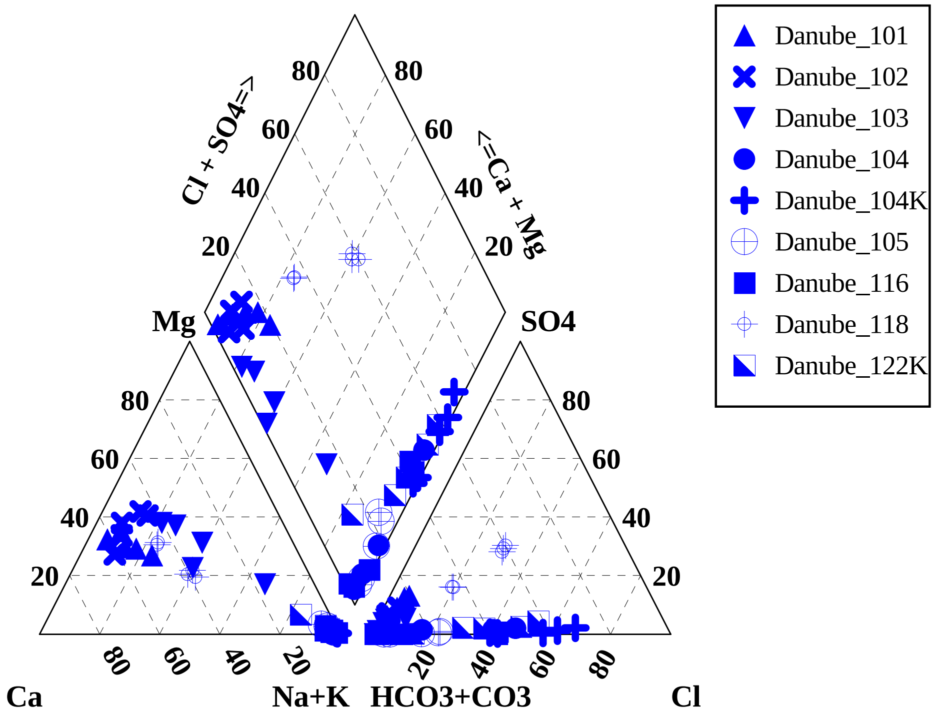

Figure 13: General groundwater composition as shown in a Piper diagram, for selected units of the Danube Basin

Legend: 101 – Quaternary; 102 – Quaternary and Upper Pannonian (cold and lukewarm waters); 103 – Upper Pannonian (cold and lukewarm waters); 104 – Upper Pannonian (thermal waters); 104K – mixed, Upper Pannonian (thermal waters) and Lower Pannonian; 105 – Upper Pannonian (cold and thermal waters); 116 – Miocene older than Badenian; 118 – Eocene; 122K– Palaeozoic

Within the Danube basin region, a smaller territory of the Lutzmannsburg-Zsira area represents a special hydrogeological environment. The connection of the Devonian thermal karst with the Miocene-Pannonian porous thermal water reservoirs is still not known in details. There are famous spas on both the Austrian and Hungarian sides which utilize these thermal waters. The Lutzmannsburg spa in South Burgenland discharges the Pannonian and Miocene aquifer, while the Bük and Sárvár spas use both the Devonian karst water and connected Badenian reservoirs, and the thermal water from the seaparated Pannonian porous aquifers. The Hungarian groundwater level monitoring well Zsira-1 is situated along the border and is screened on the same porous Pannonian layers as the Lutzmannsburg spa wells. The monitoring well measures the effect of thermal water extraction.

Significant changes in groundwater chemistry have been observed at Bük and were reported already by Klopp and Horváth (1996). An increase in TDS content of the wells which captured both the karstic Devonian and the porous Badenian and Pannonian layers was detected. The Na-Ca-HCO3 chemical type groundwater in well K-10 did not change during these years, while groundwater in well K-4 has changed to Na-HCO3(Cl) chemical type. The general TDS content increase is due to a pronounced increase in the Cl and Na concentration, and increase in the HCO3 and SO4 concentration. At the same time the content of Ca decreased. The new water composition is not typical for karst waters, but may be linked to “recharge” from the Neogene (probably Badenian) aquifers. These Neogene aquifers are presumably closed, stagnant aquifers with a high salinity. A mixing ratio was estimated based on the Cl concentrations and checked with the δ18O data. The ratio of the Cl concentration of the groundwater in well B-4 between 2011 and the time of the well construction in 1957 is about 5.8. If we assume the Cl concentration for the stagnant groundwater in the Badenian aquifers to be around 25000 mg/l, then we can expect a mixing of about 90-92% from the Devonian, Pannonian aquifers and 8-10% from the surrounding stagnant zones. The general groundwater composition is shown on Figure 14.

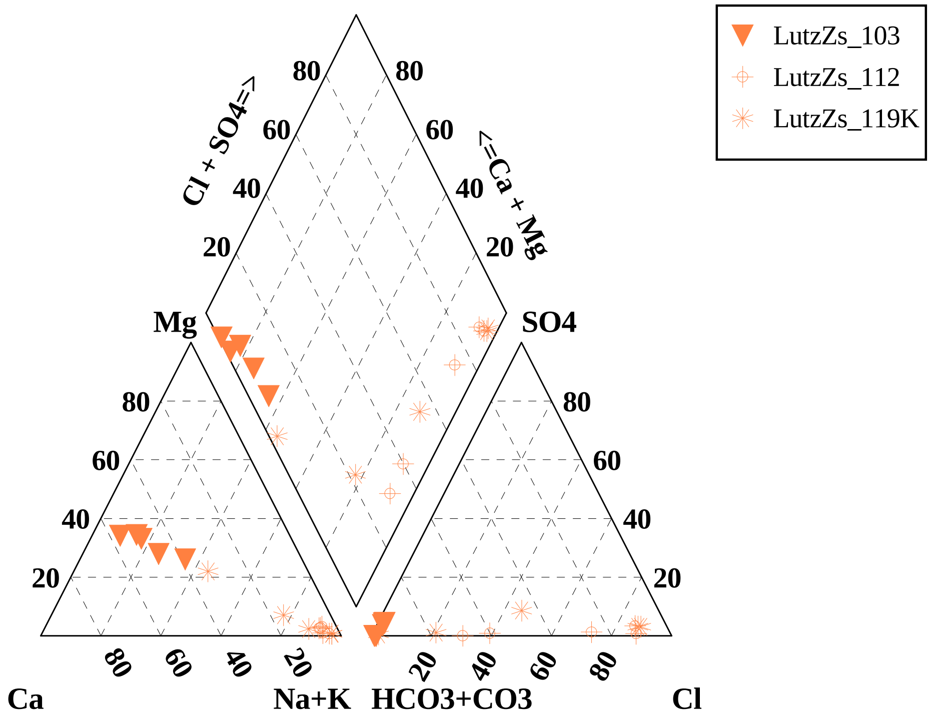

Figure 14: General groundwater composition as shown in a Piper diagram, for selected units of the Lutzmannsburg-Zsira region

Legend: 103 – Upper Pannonian (cold and lukewarm waters); 112 – Badenian limestone; 119K – mixed, Devonian and Miocene-Pannonian

3.2.5.Transdanubian Range

The Transdanubian Midmountains compose the southeastern border of the TRANSENERGY project area. The bulk of the mountains is formed by Upper Triassic platform carbonates, subordinately of pelagic then shallow water Jurassic marls, carbonates and shallow water Cretaceous sediments. The Mesozoic formations outcrop in along a SW-NE strike. Overspreading its surface outcros, the Mesozoic formations continue in the basement of the Neogen basins, in the basement of the Zala Basin to the west. East of the Rába Line the Mesozoic formations compose the basement of the Kisalföld Neogene Basin and continue northward below the Neogene sediments in the Slovak part of the TRANSENERGY region (Komarno block) (Figure 15).

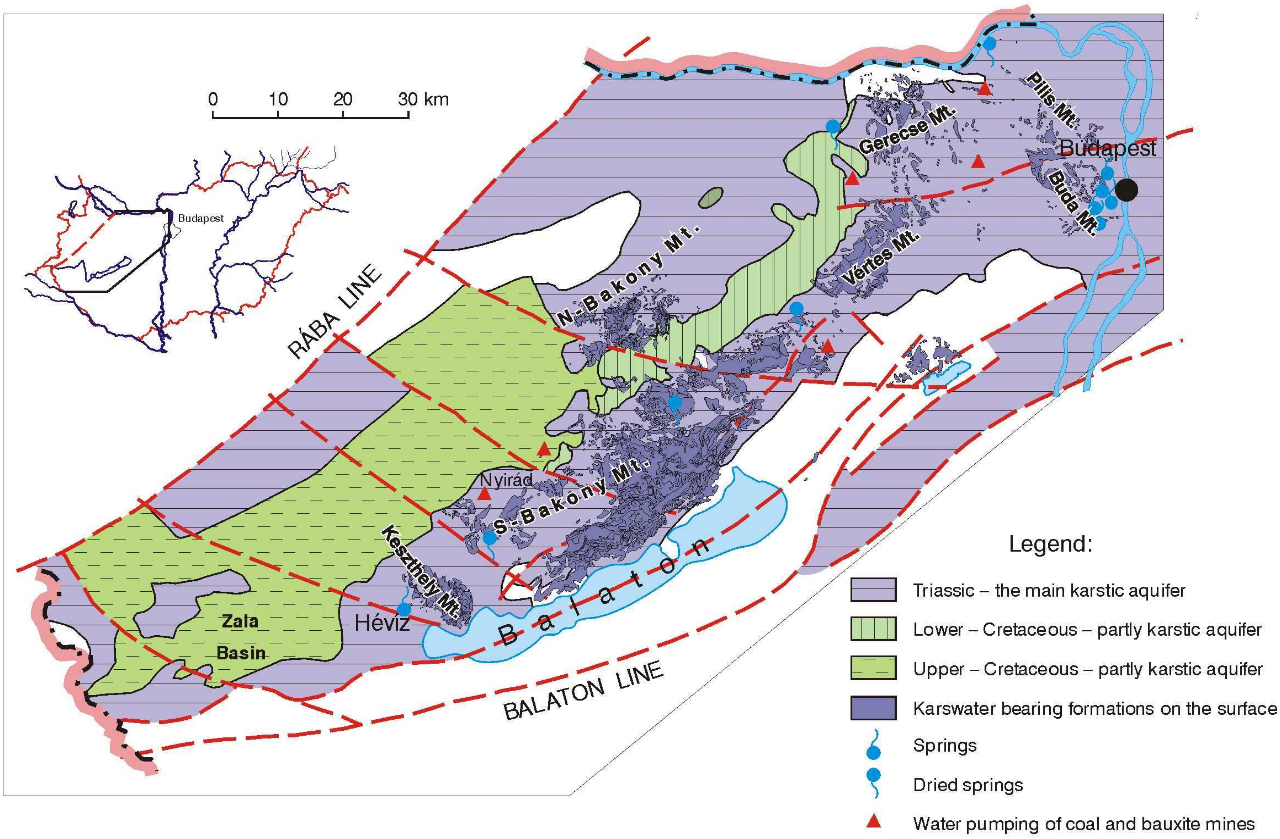

Figure 15: Extent of the karst aquifers of the Transdanubian Range in Hungary (Jocháné Edelényi E. 2009)

The most important aquifers are the Upper Triassic limestones and dolomites forming a single hydraulic and groundwater flow system over the region. The karstified carbonate rocks have a thickness of several thousand meters. The multi-phase tectonic movements resulted in the formation of a fractured system, which determines the groundwater flow system. The upper karstified part of the Triassic limestones and dolomites has higher permeability then the lower part. Along larger tectonic zones exceptionally good aquifer zones might develop. Due to overthrusting, the continuity of carbonate aquifer bodies is interrupted by Lower Triassic aquitards or marl beds, related to dragged away zones. Thus, the hydraulic conductivity along certain faults might be limited. The bulk of groundwater can only move along the strikes of thrust zones in the reservoir towards the natural discharge sites.

The average porosity of the reservoir is 2.3-2.5%. The transmissivity of the carbonate rocks varies within 5 orders of magnitude (0.3-7000 m^3/d). In case of large water level fluctuation in certain tectonic zones, this value can be even higher than 10 000 m^3/d. Such high conductivity zones are the NW-SE striking transverse faults, while the longitudinal faults are of aquitard character.

In natural conditions the precipitation is infiltrating through the outcrops of the karstic aquifer. Most of the water flows through the deep carboniferous basement, warms up and enters the surface in karst springs at the margins of the mountain region. The main regional discharges of the SW-ern part of the carbonate reservoir are the spring of the Héviz Lake, springs at Tapolca, and Tapolcafő. The main regional discharges of the NE-ern part are the springs of Bodajk, Tata, Dunaalmás, Patience, Esztergom and Budapest.

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The most important part of the Transdanubian Range is the Komarno-Sturovo area where the karstified Triassic limestones and dolomites form the main transboundary thermal water reservoir.

From a hydrogeothermal point of view, the thermal water reservoir is divided into a high and a marginal block (Franko et al. 1995). Cold karstic waters infiltrate in the southern part in the Hungarian side in the Gerecse and Pilis mountains, leading to a cooling down of the thermal water. The infiltrated meteoric water is transported to deeper zones along hydraulic flow paths, and is gradually heated up. Thermal springs occur along the edges of the hills. The Komárno high block has a fast water circulation and is considerably cooled (temperature is 20 – 22°C at a depth of 600 – 800 m, 24,5-26,5°C at 1100-1300 m, and around 40°C at 3000m). The Komárno high block is encircled by the marginal block in the west, north and east and contains groundwater with a temperature exceeding 40°C.

The Komárno block contains four chemical types of geothermal water (Franko et al. 1995), clear Ca-Mg-HCO3 type, unclear Ca-Mg-HCO3 type, transient Na-Ca-HCO3-Cl type, and mixed type dominated by Ca-SO4. All four types of thermal water are genetically associated with the Triassic dolomites and limestones of the Transdanubian Range, the first two of them being present in the Komárno high block and the transient and mixed types in the Komárno marginal block.

The effects of groundwater extraction connected to the dewatering of coal and bauxite mines in the Transdanubian Midmountains affected the entire karst water system. The predominantly lukewarm springs at the foothills have been dried up since the 1950's – 1960's (Esztergom, Dunaalmás, Sárisáp, Tata, Zámoly), or their yield has decreased (thermal karst springs at Budapest). These changes did not effect the chemical composition, except where seepage of shallow groundwater or surface water from the Danube could enter into the deeper aquifer.

The lukewarm springs of Esztergom represent one of the important discharges of the thermal karst system. Both their temperature and chemical composition (CaMgHCO3 type) are similar to the other lukewarm springs in the Transdanubian Mountain Range. The general groundwater composition in the karstified Triassic limestones and dolomites which form the main transboundary thermal water reservoir of the Komarno-Sturovo region is shown in Figure 16.

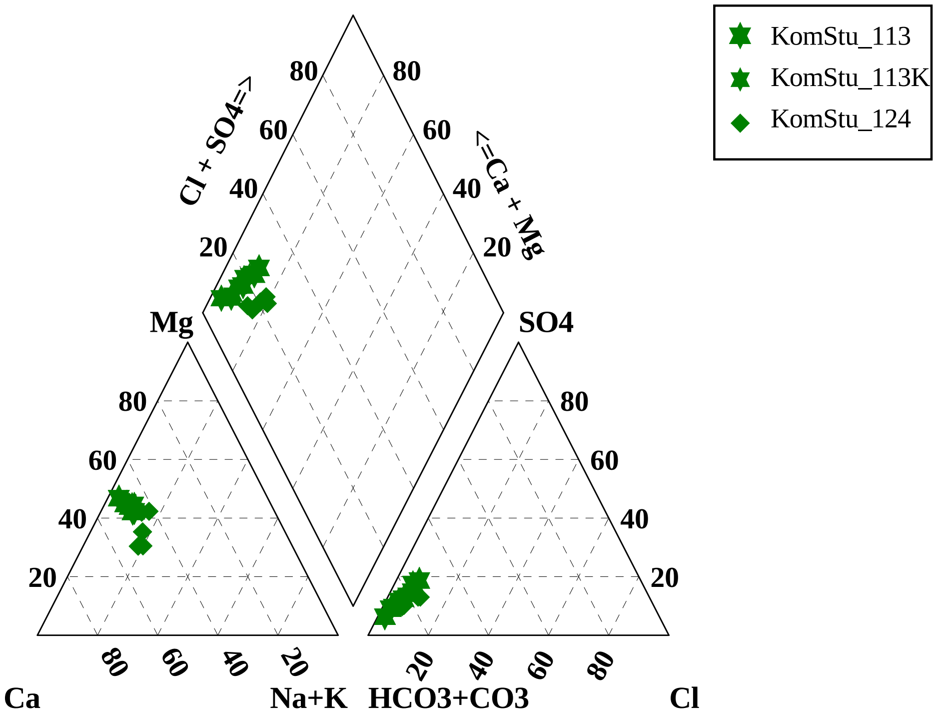

Figure 16. General groundwater composition as shown in a Piper diagram, for selected units of Komarom-Sturovo region

Legend: 113 – Upper Triassic karstic limestone and dolomite, Upper Cretaceous Ugod Limestone; 113K – mixed, Upper Triassic karstic limestone and dolomite, Upper Cretaceous Ugod Limestone and Eocene, Oligocene, Miocene; 124 – Mesozoic (in general).

3.3. Reginal hydrogeochemistry

A hydrogeochemical evaluation was carried out based mostly on the existing archive data, but additional samples were also collected in those areas where a lack of information was considered the most critical. The main aims of making new analyses were to provide help in understanding the regional flow systems and to ensure independent parameters for the hydrogeological flow and transport modelling. In those areas where either mining or intensive and continuous thermal water extraction has caused groundwater level drawdown or the disappearances of springs, the data from the newly collected samples could help in the evaluation of the effects.

In total more than 1700 archival data and the analysis of 44 newly collected samples were considered in the hydrogeochemical evaluation of the project area. All the data form part of a common multilingual database with harmonized datasets. An earlier report (Mikita et al. 2011a) describes the data structure and the distribution of data according to different classifications. An overview of the new sampling and additional data collection was also reported separately within the WP4 activities (Mikita et al. 2011b).

This chapter intends to give a brief, general overview of the hydrogeochemistry of the TRANSENERGY supra area. It focuses on the presentation and interpretation of chemical and isotope data which were considered to be the most relevant in the development of a hydrogeological flow and transport model for the supra area. These data helped in the calculation of the possible different mixing zones, which in turn could be used for the calculation of groundwater ages at the main discharge zones, and helped the model calibration process.

In the Quaternary and Pliocene aquifers a Ca-Mg-HCO3 water type prevails. In the upper part of the Upper Pannonian a developing trend of (calcium to sodium) cation exchange is typical due to the longer retention time of groundwater. The water type evolves from Ca-Mg-HCO3 to Na-HCO3 in deeper levels. The deeper Upper Pannonian aquifers store alkaline Na-HCO3 thermal water, where cation exchange has mostly finished. Locally, this water is enriched in chloride or sulphate anions, mostly due to mixing. Water stored in the marly, clayey Lower Pannonian formations is a rather isolated brine of Na-Cl type. In contrast, the sand bodies of the turbidites in the Lower Pannonian formations store water which is less isolated from its surroundings and is often mixed with other groundwater from Miocene aquifers, therefore anions show a wide range of values. The Middle Miocene formations store different waters depending on their burial depth. Where layers outcrop the infiltrating Ca-Mg-HCO3 water is observed, while towards deeper parts the longer retention time, cation exchange, mixing, dissolved gas and other geochemical processes modify its composition, so Na-HCO3 to Na-Cl types prevail. Some of the thermal aquifers both in the intergranular Neogene sediments and in the basement have no active recharge and store brine-type Na-Cl waters. The Palaeozoic metamorphic rocks usually do not represent important geothermal aquifers, but the thermal water in the Raba fault zone, is alkaline to Na-Cl type, and highly mineralized.

4.General concepts of the hydrogeological numerical model

As it was discussed in the previous geological and hydrogeological chapters the hydraulic and thermal systems of the NW Pannonian Basin consist of two separate groundwater flow systems, the porous system and the basement system.

The more or less separate Neogen sub-basins of the NW Pannonian Basin are filled with porous sediments in great thickness. Some part of these porous sequences are important thermal water aquifers. Despite of the different hydrogeological characteristics and conductivities of the layers, the whole Neogen porous system forms a uniform hydraulic system, in which separate, sometimes several hundred meter thick aquifer and aquitard layers alter.

The basement formations consist of metamorphic crystalline and carbonate rocks. Basically the crystalline rocks cannot be considered as real aquifers, but the fissures of the rocks can be have higher conductivity, especially in the upper weathered zone. The most important thermal water aquifers of the basement are the carbonate formations. Sometimes they can be characterized as fissured aquifers, but usually they were karstified during different stages of geological history.

These two systems (porous and basement) are separated by thick lower Pannonian and Miocen aquitard formations, and therefore form independent thermal water systems. These systems needed different approach in the modeling, so two different models were developed, however they have been merged together at the end of the modeling work.

4.1. Strategy and basic steps (workflow of the construction of the Supra model)

First a simple horizontal unconfined one-layer flow model was constructed for the determination of the groundwater table of the total area. It was important, because later on the computed head of the first model layer served as a boundary condition for the deeper model layers. The thickness of this preliminary model layer was extremely large, thousands of meters, eliminating the effects of the land surface variability. It also meant that this layer was only the equivalent of the more or less realistic 10-30-50 m thick shallow water table aquifers. The transmissivity of it was the same, this way the conductivity was 2 order magnitudes less.

The calibration of this model was based on the permanent creeks and rivers, looking whether they have or have not crossed the equipotential lines. If not, we had to change the hydrogeological parameters (decrease the conductivity that region). When we reached a relatively good pattern in a subregion, we got the typical or representative transmissivity values. This procedure was applied only for hilly and mountainous regions. Later on this value helped to determine the conductivity values of the geological formations in the shallow subsurface. In the lowland areas and larger alluvial parts of the Supra Area, shallow monitoring wells and formerly constructed groundwater table maps were used for calibration.

In the second phase we started to build 3D model. First we inserted the existing layer into a two-layer system. The upper 30 meter thick layer represented the water table aquifers, and the lower layer represented the entire system below it. In this case we increased the conductivity values in the upper layer, which characterized the realistic, or known values. After some running, with using the „trial and error", we got a more or less calibrated K parameter zones in the first model layer.

In a large region, with high surface elevation variability the determination of the unconfined parts was difficult. During running processes we changed the unconfined character to confined several times, preserving the bottom of the model layer, but cutting the top-most surface level to identify the unconfined parts in a more reliable way.

During the third phase we chose the pre-Upper Pannonian surface (base of the Upper Miocene porous aquifer complex) as the bottom of the model. Then inserting the pre-Quaternary surface under the first model layer (unconfined unit) and split the Pannonian sequence into three even thick layers (strata between the pre-Quaternary and pre-Upper Pannonian surfaces) a five-layer model structure was achieved. Afterwards, based on our former experiences from other modeling of the Pannonian-basin, the uppermost Panonnian layer was further split into two even layers. The reason is that this upper layer is intensively used in Hungary and partly in Slovenia for cold water abstraction. Consequently at the end of the procedure we constructed a 6-layer model, encompassing the porous regional flow system.

The assigning of conductivity values of the layers was simple at the beginning: each layer got a global horizontal K value, with a global anisotropy. (For the vertical conductivity usually 3 orders of magnitude lower value was chosen than the horizontal one. The prior values came from our former large-scale modeling experiences, mentioned above).

In the porous aquifer complex we used some existing reconstructed equipotential maps for the cold and thermal confined system. Monitoring well data were used only for those parts, where reconstructions did not exist for the pre-exploited state. In the case of the deeper, high temperature zones, we had to correct the measured heads and pressures, taking into consideration the vertical distributions of the density. In this part the density usually decreases with depth, because of the high temperature gradient and a relatively low salt content. (There are no any sign of free convection here, because of the low vertical conductivity of the porous basin fill sediments). At the end of the mentioned correction procedure, we got the so called environmental head relative to the shallowest cold parts (Lusczynski 1961).

In the fourh phase we built the model further down to the basement and to the total depth(9 km) of the model.

Below the porous aquifer complex we put the Lower Pannonian, Sarmatian, Badenien, Lower Miocene, and Upper Cretaceous layers, first as a homogenous, low conductivity and strongly anisotropic system. The process of determining the conductivity values was the same as it was in the case of the porous aquifer complex. At the beginning we used global values, followed by calibration, and after arriving to the best realization, a detailed mosaic-like hydrostratigraphy was put into the model. For this purpose we used the hydrogeologically qualified geological formations from the „flying carpet geological models.

The basement was split into an upper aquifer with better permeability, and into a lower one with poor permeability. The upper basement aquifer got unique parameters, however in reality it consists of regionally altering sub-systems with good (weathered, karstified mantle) and poor permeability. Furthermore in some sub-regions this unit is connected to the first permeable sediment layer. These interconnected basement and sedimentary reservoirs are of great importance.

For the calibrations of the basement aquifer complex, the reconstructed original, pre-exploited karst-water table maps, and some monitoring points were used. In the vicinities of larger thermal and luke-warm springs, the chemistry and the isotopic composition were used to give information about the mixing processes around the springs.

The mixing processes (mixing corrosions) are important for porosity-permeability creation in hypo-karst systems around the larger springs (e.g. in the surroundings of Hévíz Lake spring).

Mixing of different waters was evaluated based on hydrogeochemistry and isotope composition at Hévíz Lake, Baden, Bad Vöslau, Tata-Patince and Esztergom-Sturovo thermal karst spring areas considering information from the neighboring wells.

During later construction of pilot area models, we will use age indicator components like δ18O and 14C isotope data from the harmonized database and from new additional water sampling of the TRANSENERGY project.

4.2. The model grid

The first step in creating the conceptual model is the vertical and horizontal outline of the model area, i.e. to define natural model boundaries where it is possible. During outlining several aspects were taken into consideration, such as the geological framework together with the main tectonic structures, recharge areas, and rivers as discharge places of groundwater, groundwater bodies, groundwater divides. The final borders of the model area consist of the mixture of the different boundary types mentioned above.

The selected model area covers the entire TRANSENERGY project area, including the major porous thermal water bearing basins of the NW Pannonian Basin, and some extensions to the nearest mountain-basin borders and to some neighboring areas taking into account the horizontal flow entering through the defined model border.

The horizontal extent of the model is a rectangular area, in UTM projection, where the corner points are the followings:

Easting (X): 487 500 and 801 500

Northing(Y): 5 122 000 and 5 405 000

Size of the model area: 283 × 314 km

Horizontal resolution (grid size) of the model is 1000 × 1000 m

The depth of the model is determined by the base of the regional flow system. To prepare a completely coupled flow and heat transport model, the upper 8 km of the subsurface was assessed.

4.3. Hydrostratigraphic (HS) units

The hydrostratigraphic units represent rock bodies (geological units) with similar hydrogeological properties. They are defined on the basis of well-known stratigraphical units, and may comprise a wide range of different formations. Most of the hydrostratigraphical units are not found everywhere in the entire supra-region.

The hydrostratigraphical units of the supra-regional model area are the following:

- –Quaternary formations in the deep basins
- –Upper Pannonian sediments
- –Lower Pannonian / Post Sarmatian Miocene sediments
- –Sarmatian sediments
- –Badenian sediments
- –Lower Miocen formations
- –Carbonate basement formations (mostly Triassic karstified limestone and dolomite complex
- –Fractured crystalline basement

4.4. Boundary conditions

4.4.1.Recharge

The main recharge areas are represented by the higher elevated regions where the older geological strata are outcropping on the surface. They are mostly situated at the margin of the model area, but there are some smaller areas inside the model region where recharge can take place (for example Sopron Mountains, Leitha Mountains, Male Karpaty, Zala Hills, etc.).

The covered geological map served as a basis to delineate the different recharge zones based on the different surface lithologies, combined with the important meteorological data (precipitation and temperature).

The different geological formations of the joint and harmonized surface geological map were qualified, based on the similarities, and analogies. The qualified formations were grouped into 9 major units (Figure 17:).

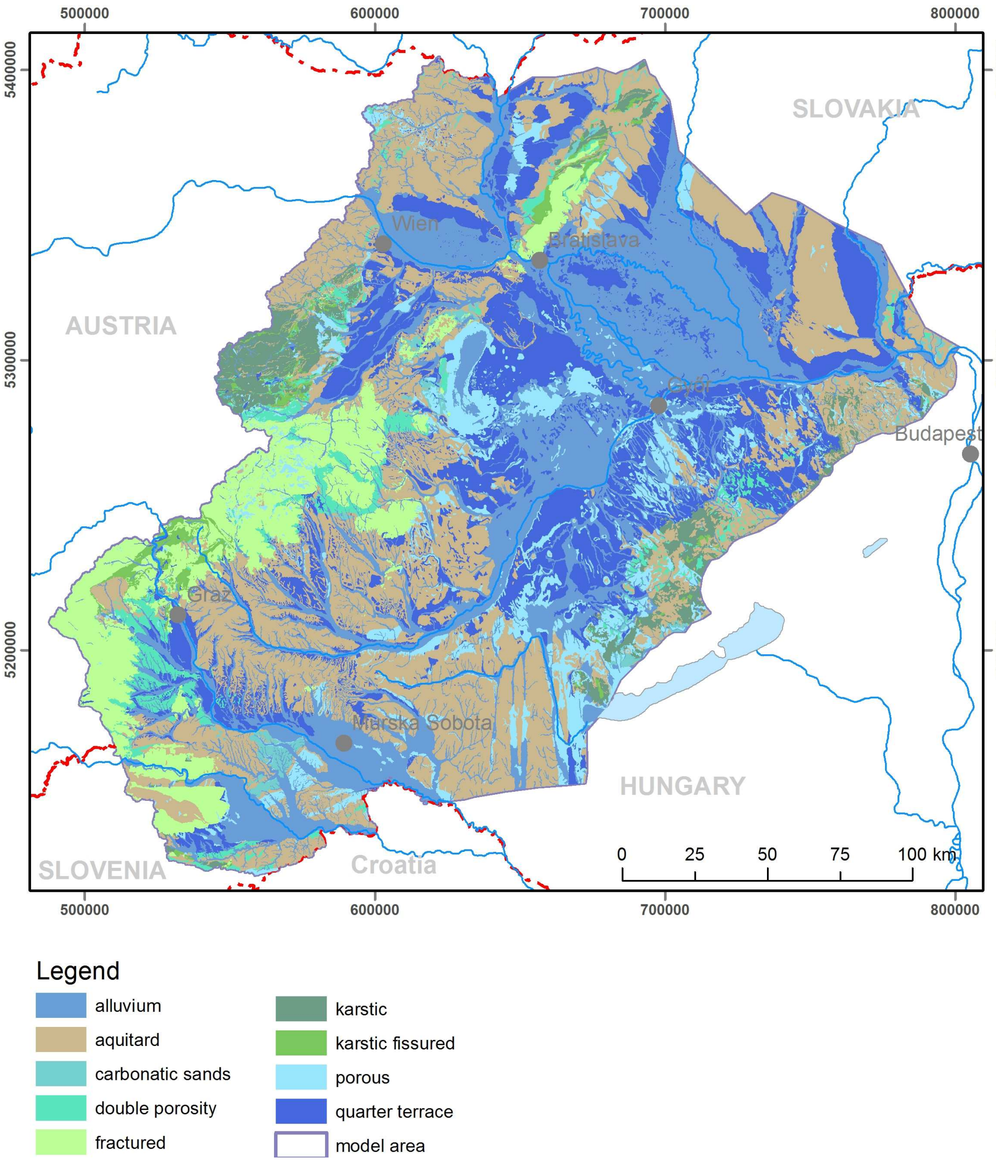

Figure 17: Recharge categories based on the surface geological map

4.4.2.Discharge

The main discharge of the porous system are represented by the rivers and the alluvium of the main rivers. The discharge areas are show non Figure 18.

The springs are important local discharge points. The catchment areas are usually several order of magnitude bigger, than the recharge areas. Very often a group of springs appear in a smaller region.

Evapotranspiration is an important discharge process. It takes place at the area of river alluviums.

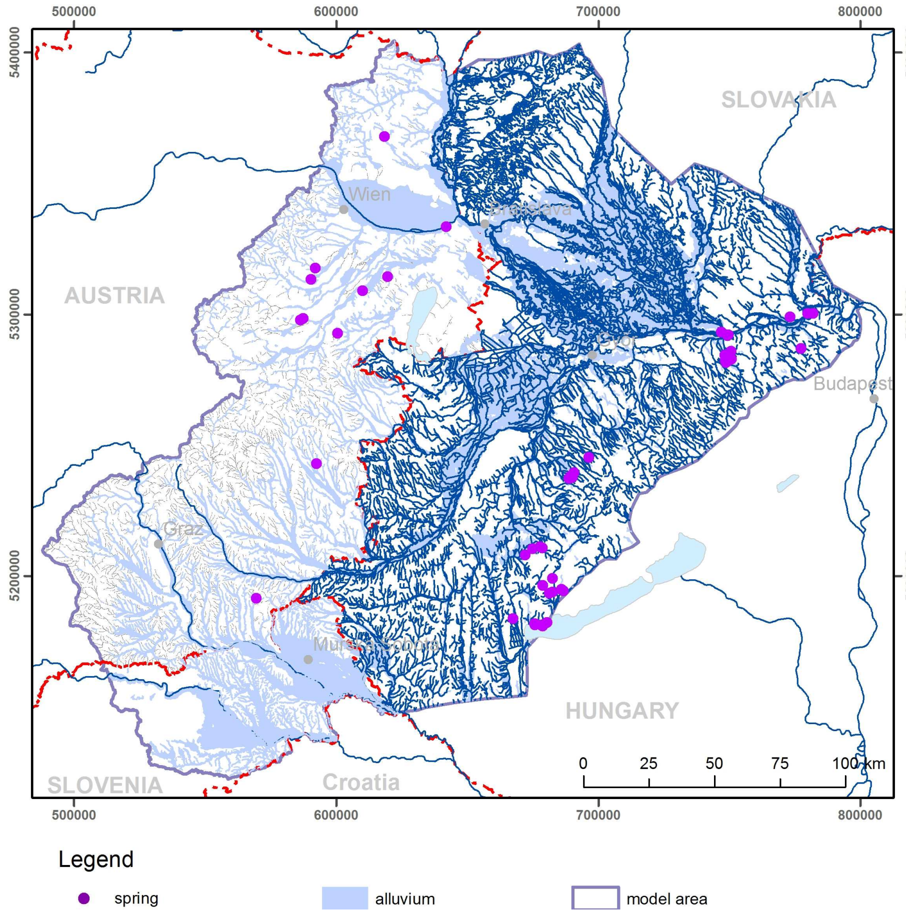

Figure 18: Discharge areas of the Supra-region

4.5. Model code

The supra-regional hydrogeological modeling was performed by Visual MODFLOW (VMOD), which is a graphical interface of the worldwide standard modelling software MODFLOW.

MODFLOW is a three-dimensional finite-difference groundwater model, which is a computer code that solves the groundwater flow equation. It has ability to simulate a wide range of different systems. Currently, there are at least five actively developed commercial and non-commercial graphical user interfaces for MODFLOW. It consists of a Main Program and a series of highly-independent subroutines called modules. The modules are grouped in packages. Each package deals with a specific feature of the hydrologic system which is to be simulated such as flow from rivers, or flow into drains, or with a specific method of solving linear equations which describe the flow system such as the strongly implicit. The division of MODFLOW into modules permits the user to examine specific hydrologic features of the model independently. This also facilitates development of additional capabilities, because new modules or packages can be added to the program without modifying the existing ones. The input/output system of MODFLOW was designed for optimal flexibility.

Visual MODFLOW also combines proprietary extensions, such as MODFLOW-SURFACT, MT3DMS (mass-transport 3D multi-species) and a 3D model explorer. Visual MODFLOW provides professional 3D groundwater flow and contaminant transport modeling using MODFLOW-2000, MODPATH, MT3DMS and RT3D.

This fully-integrated groundwater modeling environment allows to:

- Graphically design the model grid, properties and boundary conditions,
- Visualize the model input parameters in two or three dimensions,
- Run the groundwater flow, pathline and contaminant transport simulations,
- Display and interpret the modeling results in three-dimensional space.

5.Construction of numerical models

The construction of the porous and basement models were very similar. Some steps of model development were the same in the two different model types. Despite the similarities there were significant differences in the two models, which will be discussed in the following separate description of the model development.

5.1. Porous subsystem

5.1.1.Model grid

The extent and resolution of the conceptual model was applied in the porous numeric model. In the regular rectangular area of the model the specified target area was outlined by inactive cells. Inactive cells were assigned after the model grid development and all the model layers were created. Simulation of the model was carried out only for the active area.

5.1.2.Hydrostratigraphyc (HS) units

5.1.2.1.Hydrostratigraphyc (HS) units in 3D

The model layers comprise the HS units, but are somewhat different. The model-code specifies particular layers throughout the model area, so one layer can contain several HS units, or some HS units can belong to different model layers.

The major groups of hydrostratigraphic units were the following:

- Quaternary formations in the deep basins
- Upper Pannonian sediments
- Lower Pannonian / Post Sarmatian Miocene sediments

These groups were the “skeleton” of the 3D model. They were refined by further subdivision into additional layers for the better representation of the 3D flow paths, and hydraulic potential fields.

Based on the experiences of some previous regional models, a reasonable solution is to delineate first the 3D position of the shallow aquifer (first model layer), which host the groundwater table, then connect this layer to the deeper confined layers. The HS units of the first model layer are composed of the uppermost pre-Quaternary formations on the hilly and mountainous ranges, and Holocene and Upper Pleistocene alluvial and shallow terrace sediments at the valleys and valley-sides.

In order to ensure the safety numeric calculations all the underlying layers had got a minimum thickness, and the sudden changes in the depth of the layers were smoothed.

The second layer represented the Quaternary formations. The Upper Pannonian formations were divided into four equal sub-units, each represented a separate model layer. The Lower Pannonian formations were considered as the aquiclude basement of the upper porous hydraulic system.

5.1.2.2.Hydraulic and transport properties of the HS unit

5.1.2.2.1. Conductivity, permeability

The conductivity values of the model layers can not be determined solely from well hydraulic test. These test results related to a very close environment and usually represent the best available aquifer layers. In regional scale the conductivity values of a HS unit varies in wide ranges, which can be handled by using average values in the model. On the basis of the well measurements, previous flow models, earlier studies and references from literature all the partners determined the conductivity value intervals for all the layers in their country part of the model area.

The conductivity zones inside the layers are determined according to the hydrogeological characterization of the geological formations. The following hydrogeological categories were specified:

–aquitard formation
–aquifer formation
–double porosity formation
–fractured formation
–karstified formation

The applied conductivity chategories and values are shown in Figure 19-Figure 23.

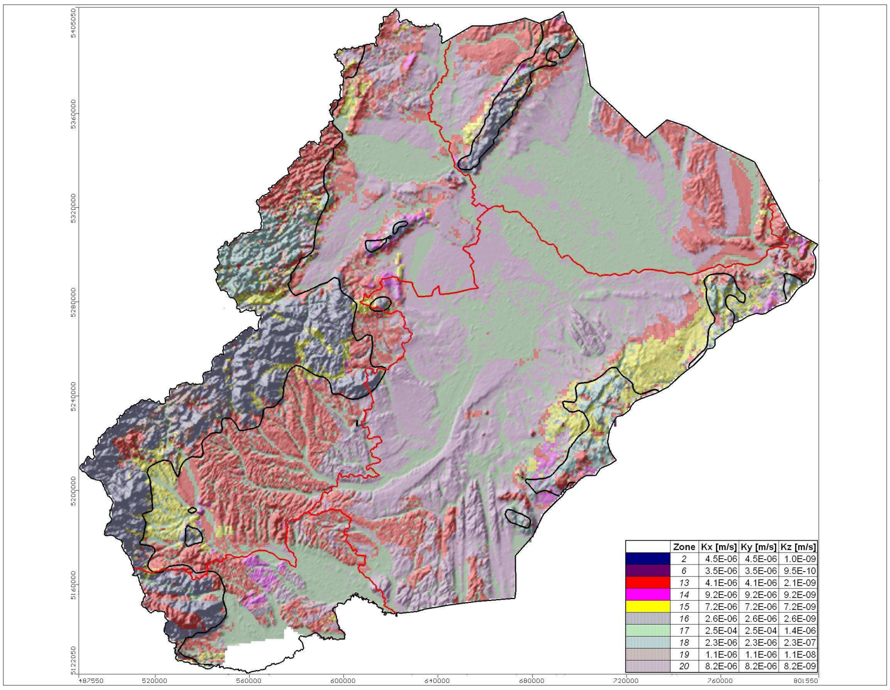

Figure 19: Conductivity categories of layer 1 (the first aquifer under the groundwater table)

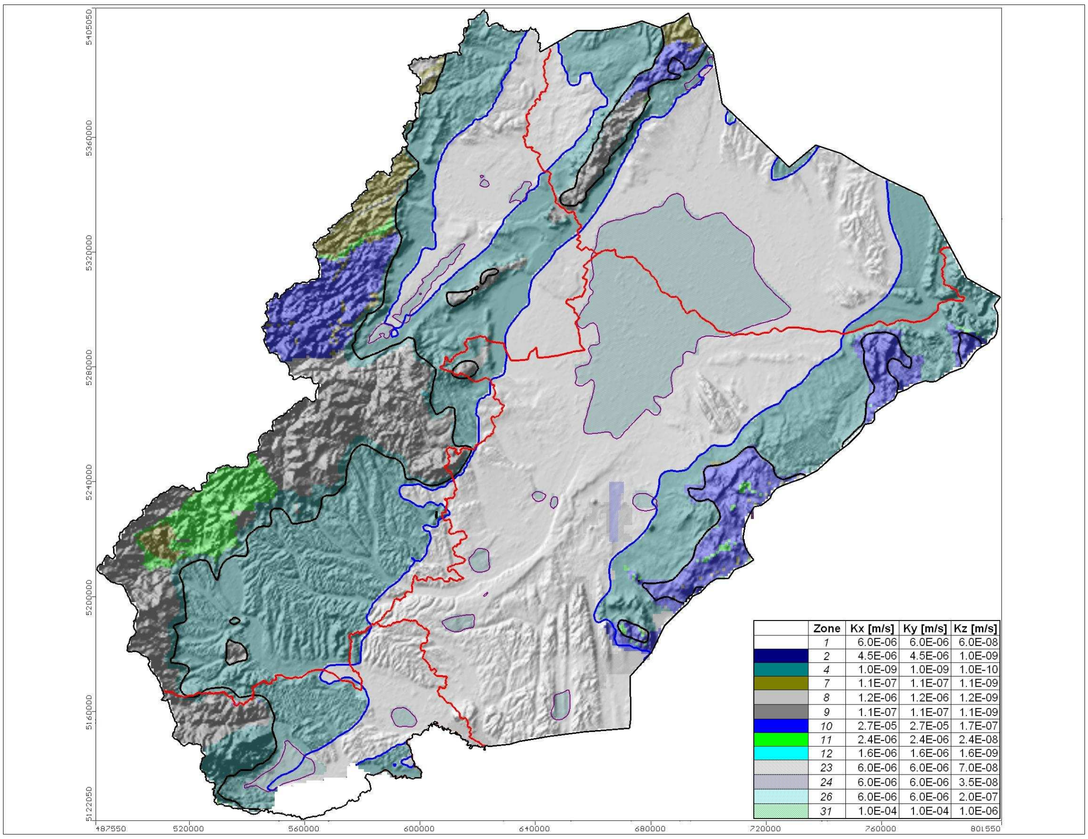

Figure 20: Conductivity categories of layer 2 (Quaternary formations)

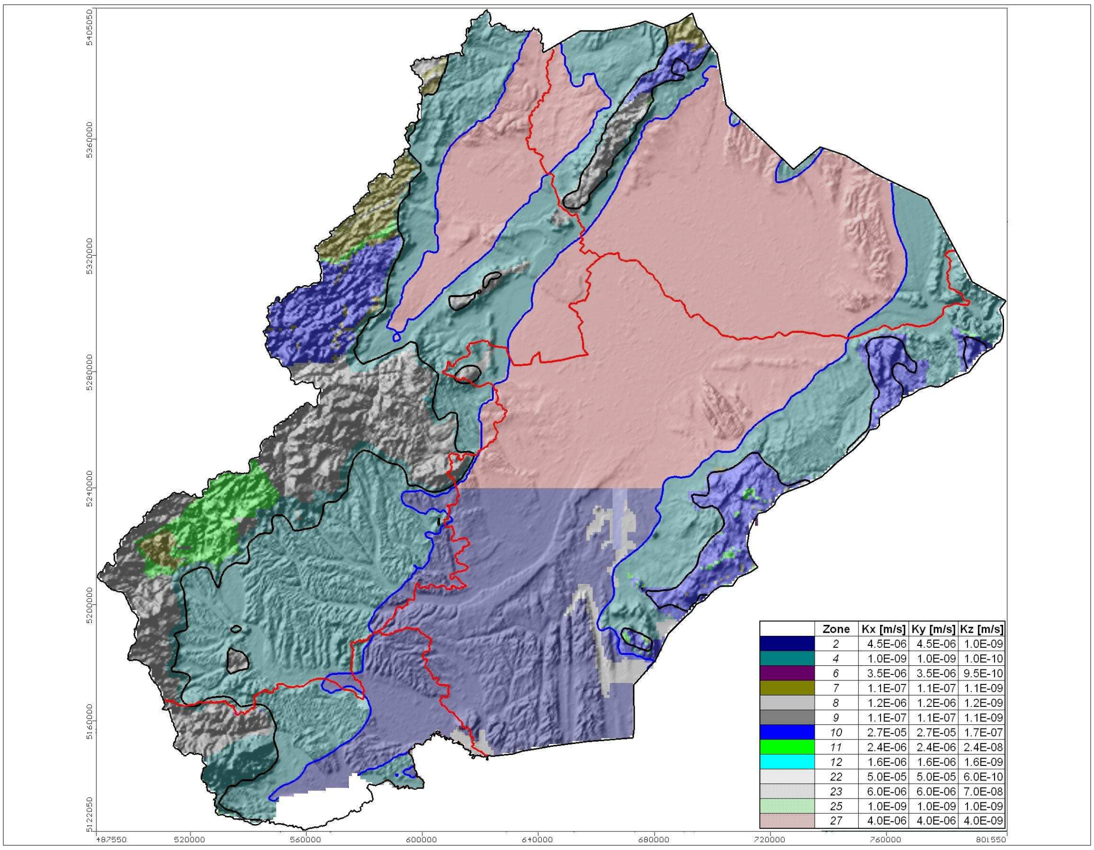

Figure 21: Conductivity categories of layer 3 (Upper Pannonian cold water aquifer)

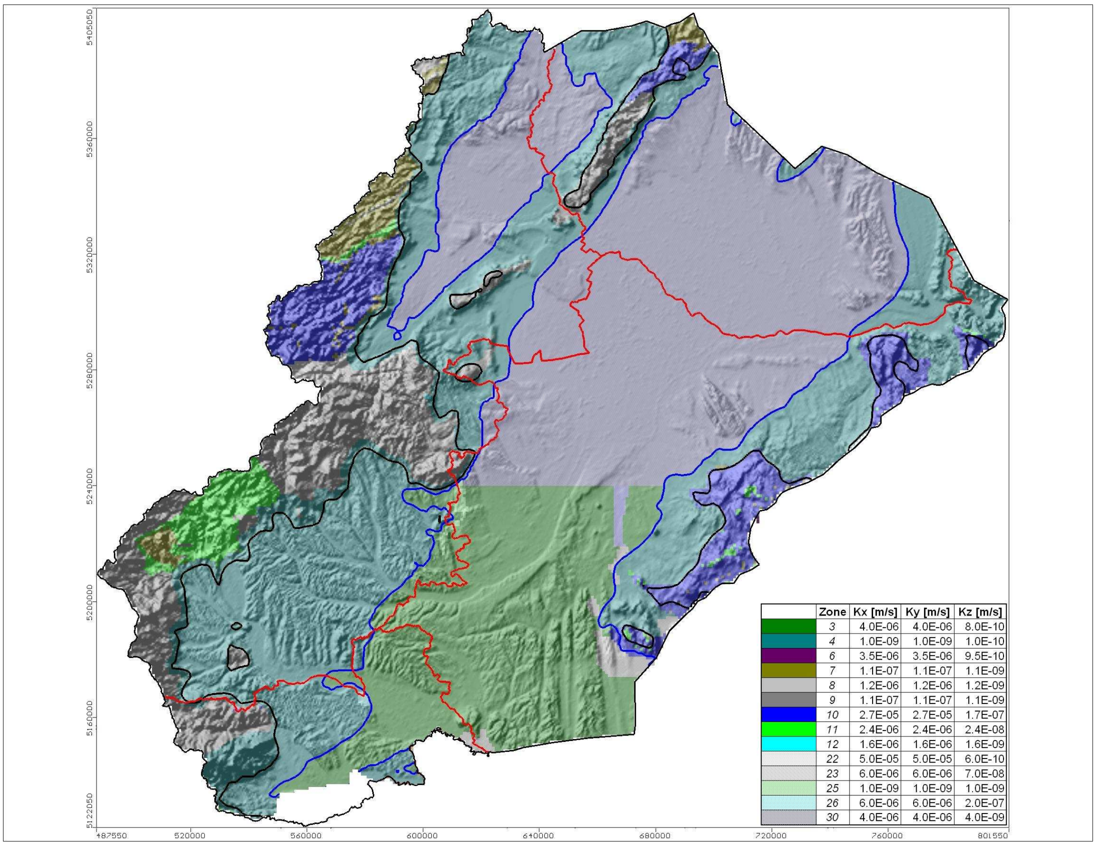

Figure 22: Conductivity categories of layer 6 (Upper Pannonian thermal water aquifer)

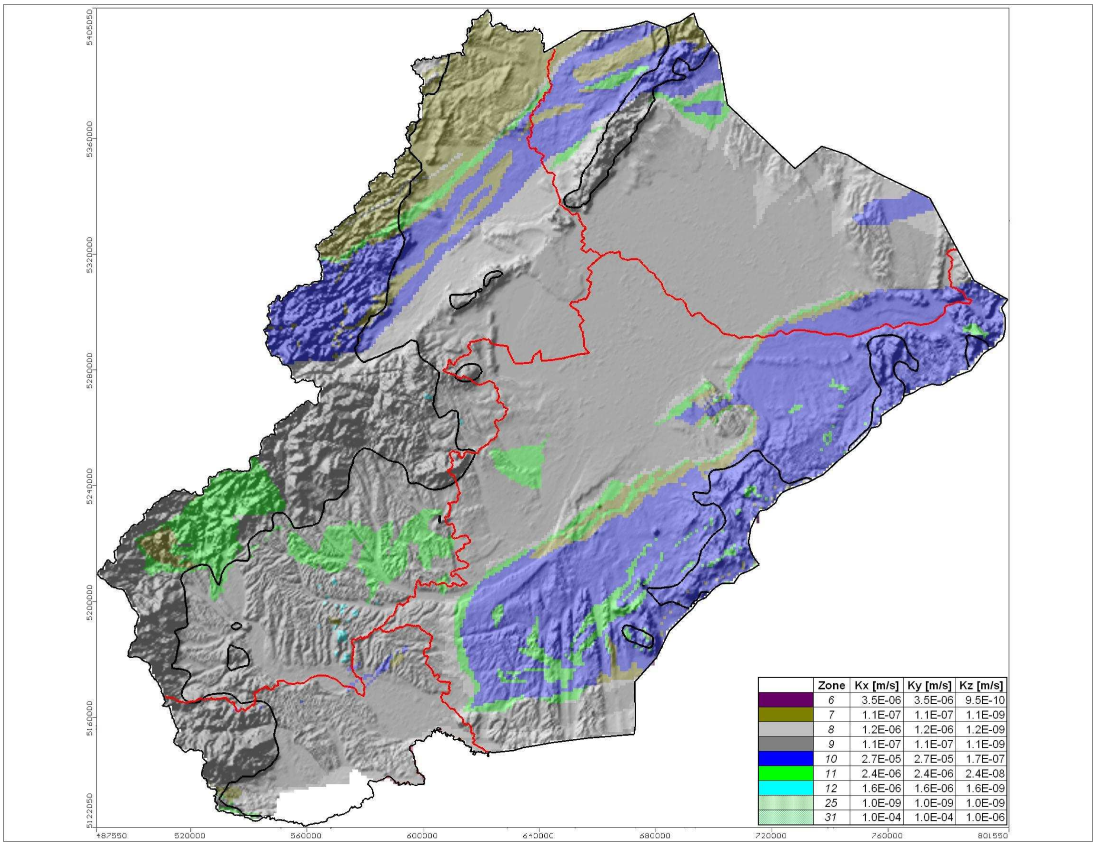

Figure 23: Conductivity categories of layer 10 (Basement formations)

5.1.2.2.2.Porosities

Porosities can derive from laboratory measurements, geophysical logs, analogies, and experiences from previous models, giving a possible range of values for regional hydogeological modeling. New groundwater samples were collected and analyzed for age indicator environmental isotopes to refine the flow velocities of the flow system, which were used during the calibration phase. A general effective porosity value (0.15) was determined during calibration phase and used for all porous model layers at the end.

5.1.3.Boundary conditions

The following boundary conditions types were used in the model:

–recharge,
–discharge (drain, river),
–no flow.

5.1.3.1.Recharge

The diffuse type of infiltration of the precipitation is the major factor controlling recharge in the regional porous model. Recharge values were determined at the entire model area as it was describe in Chapter 4.4.1.

5.1.3.2.Discharge

In this regional model the topographic surface derived from the SRTM model was used as a drain boundary condition (or seepage surface) everywhere. This kind of innovative method assigned as an upper boundary condition ensured the discharging functions of the deepest valleys. Mean water levels measured at gauging stations along the major rivers were used to control computed values.

Groundwater abstraction was not taken into consideration. The abstracted steady state model used the average groundwater levels of the last decades as natural condition. The effect of groundwater abstractions will be studied in details in the pilot flow models.

5.1.3.3.No flow condition

Both the margins and the basement of the model are represented with no flow boundary condition.

5.1.4.Running model

Modeling strategy was to start with the simplest versions and then develop to the more complex ones. Several running tests were carried out during developping the model to ensure the succesfull runing version in all phases of the development, and controlling the model preliminary results.

5.1.4.1.Calibration targets

The calculated groundwater table was compared with the existing groundwater table maps. However there were constructed maps related only to the regions of alluvial plains.

Where such maps were missing, data of shallow monitoring wells were used. The dense river network was compared to the calculated groundwater table too. The calibration objects are shown in Figure 24.

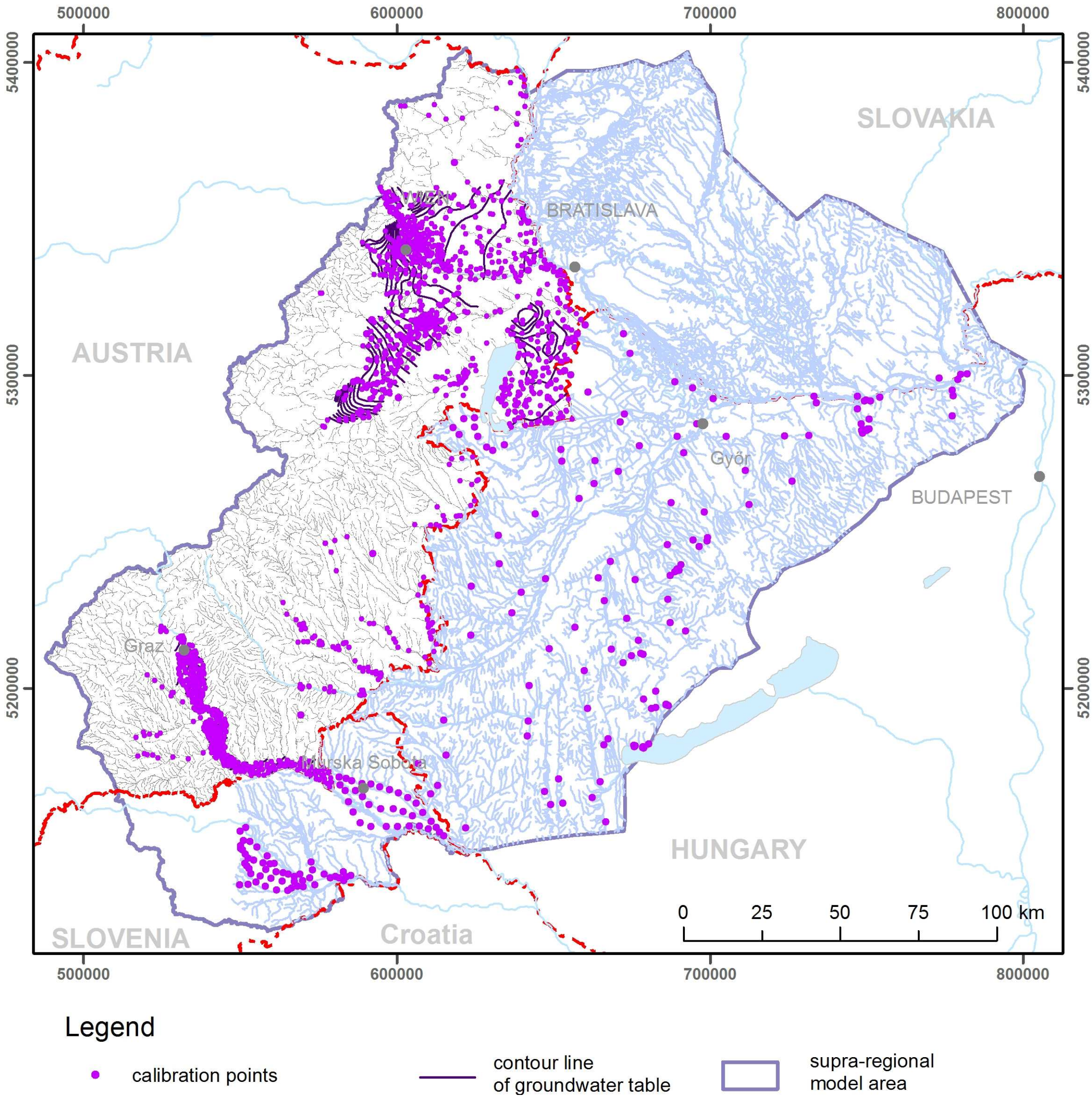

Figure 24: Elements used by calibrating the groundwater table

The hydraulic potential values of the porous model layers were compared to the measured values in monitoring wells. The average of time series of the last two decades were used for calibrating the steady state abstraction condition. In the case of the pre-abstraction, natural, or original case, the reconstructed equipotential maps were used (Figure 25).

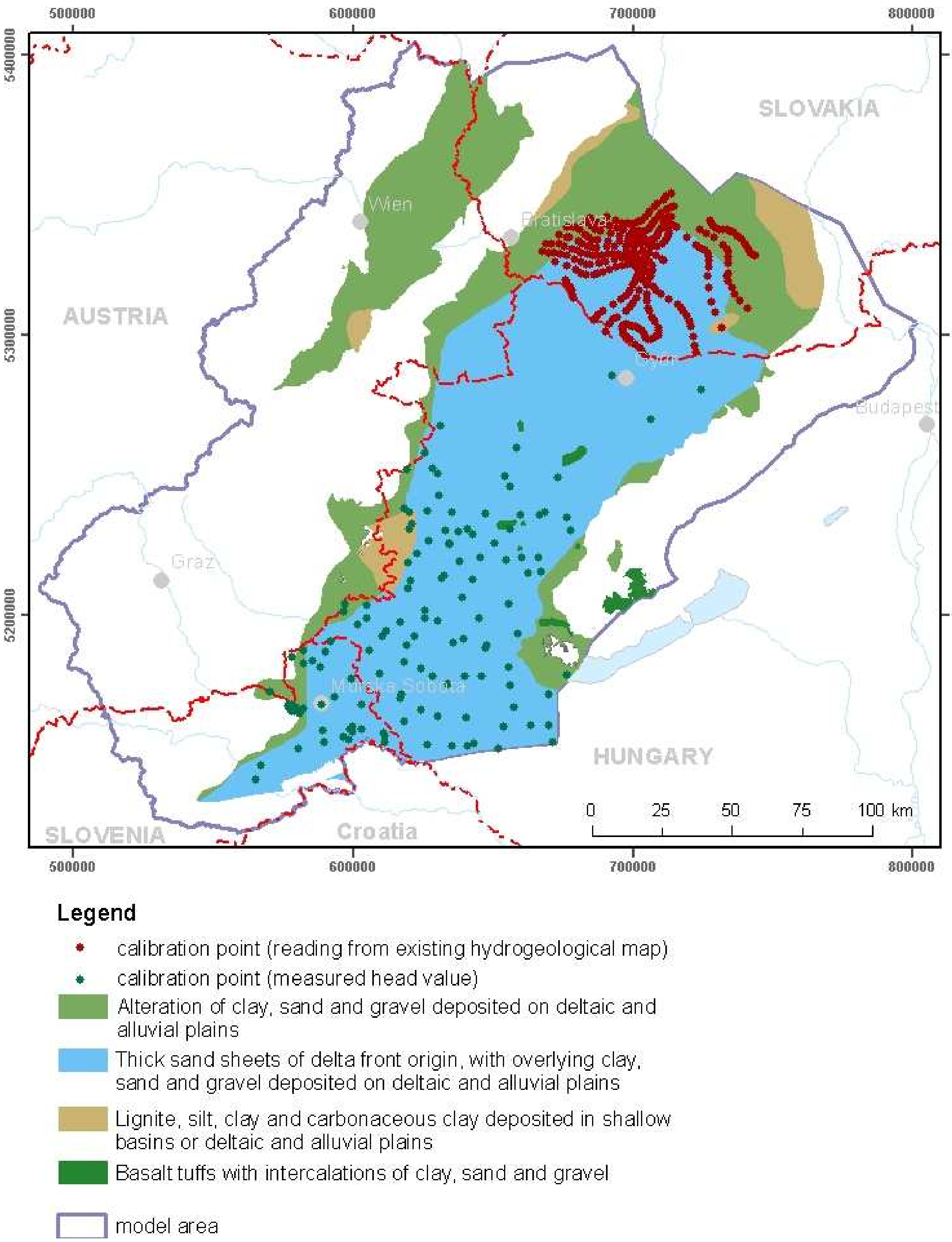

Figure 25: Elements used by calibrating the groundwater table

Groundwater ages were calculated based on stable ($\delta^{18}O$, δD, $\delta^{13}C$) and radioactive isotope (^{14}C) analyses. Where tritium data were available, those were also used as markers of fresh (last 60 years) infiltrations.

Stable isotopes were used to differentiate between the cold (Pleistocene) and warm (Holocene or older than Pleistocene) infiltrations.

The very negative values in the upper 200-300 meters of the Neogene sediment succession in the Danube Basin suggest a very slow groundwater flow rate in this area. The very low ^{14}C values support this assumption.

The calibration was taken in several steps, each step calibrated a special part of the modell. The results of the calibration of the porous model are shown in Figure 26-Figure 31.

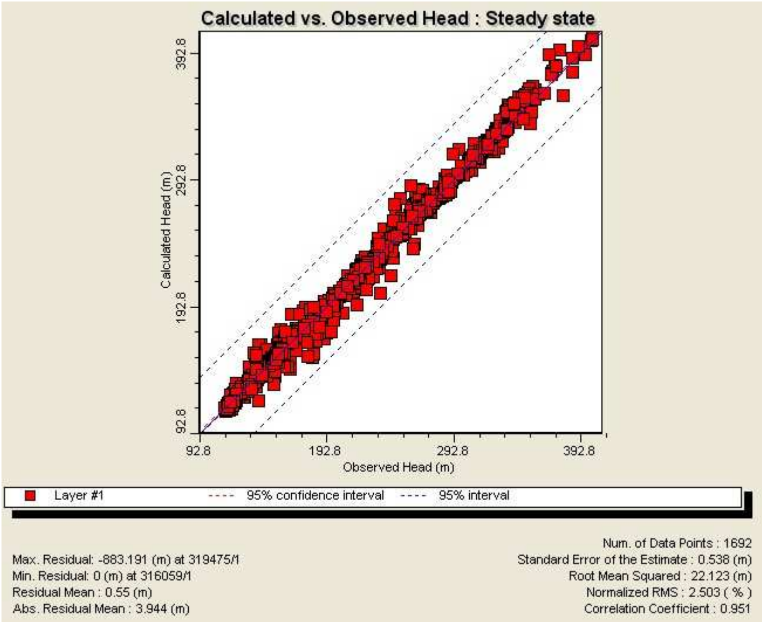

Figure 26: Calibration of the shallow groundwater table of alluvium situated in Austria

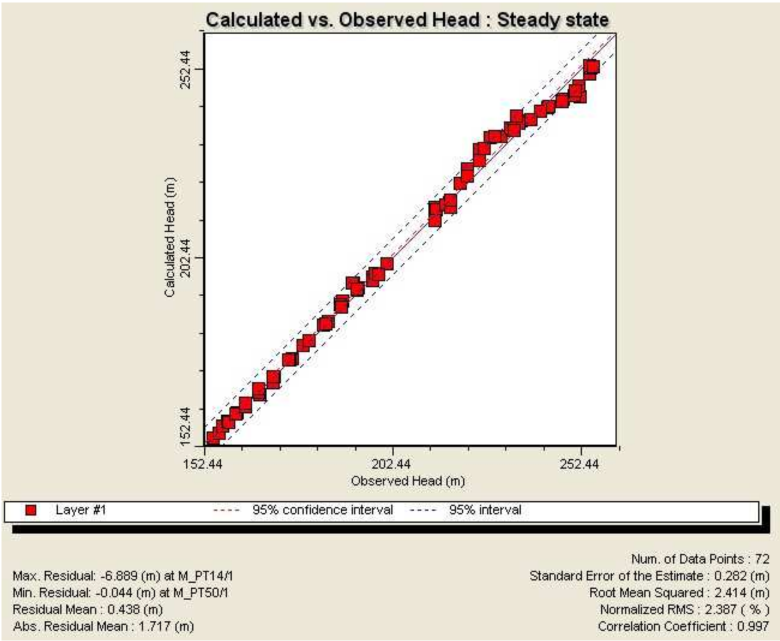

Figure 27: Calibration of the shallow groundwater table of Mura-Drava region

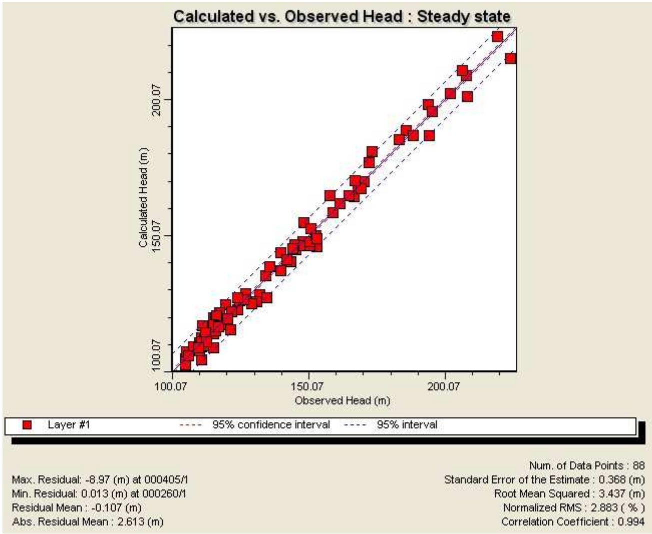

Figure 28: Calibration of the shallow groundwater table to the monitoring well data in Hungary

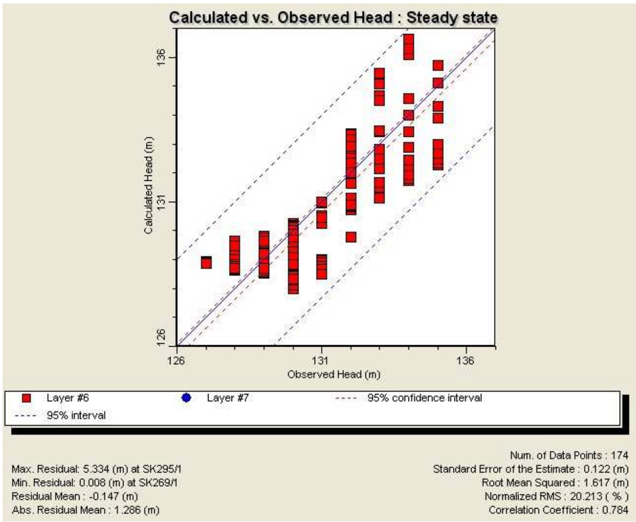

Figure 29: Calibration of the Upper Pannonian thermal water heads to the existing maps in Slovakia

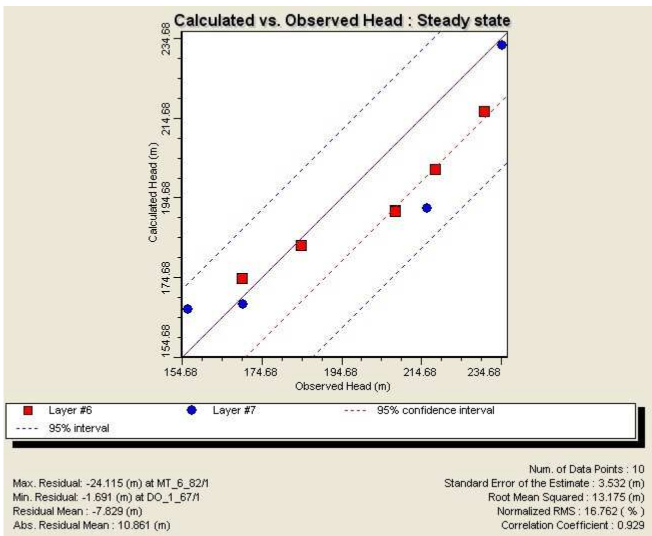

Figure 30: Calibration of the Upper Pannonian thermal water heads in Slovenia

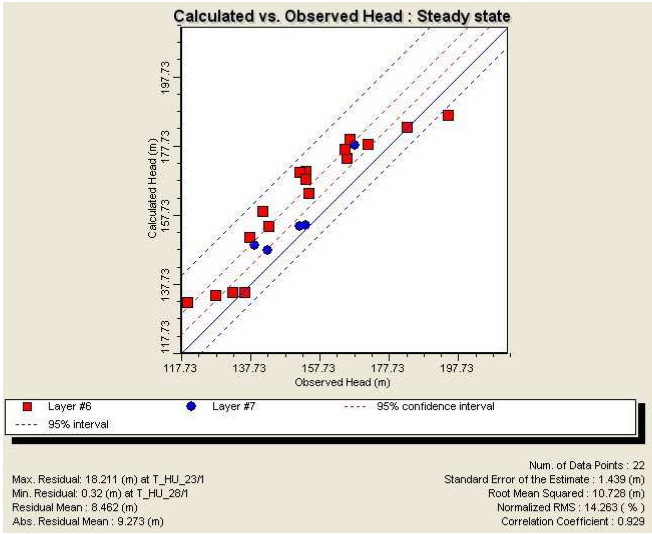

Figure 31: Calibration of the Upper Pannonian thermal water heads in the southern part of the Kisalföld in Hungary

5.2. Basement model

The basement model simulates the thermal water flow of the basement crystalline and carbonate formations (separately the upper, weathered, or karstified part from the deeper fresh part). The Miocene thermal aquifers form joint thermal system together with the basement aquifer formations, therefore they were modeled together as one unit in the basement model.

5.2.1.Model grid

The model grid of the basement model was the same like in the porous model.

5.2.2.Hydrostratigraphyc (HS) units

Only two hydrostratigraphic units are differentiated in the basement model. The 50-100 meters upper part of the basement formations were separated in a different layer. The upper part of the basement layer usually has higher conductivity both in the crystalline and in the carbonate formations. This higher conductivity is related to the weathering and karstification when the basement rocks were subaerially exposed during the geological past. The layer thickness in the model had to be increased to 500 meters to avoid numerical errors due to the great variability of the elevation of the bedrocks. Of course, parallel to the increasing thickness, the effective hydraulic conductivity, and effective porosity had to be decreased. All the other lower parts of the basement until the depth of 8 km were considered as the same basement layer.

Similar to the porous model, the conductivity zones are outlined according the hydrogeological characterization of the basement formations. The categories correspond with the applied ones in the porous model.

The different conductivity zones and values are shown in Figure 32.

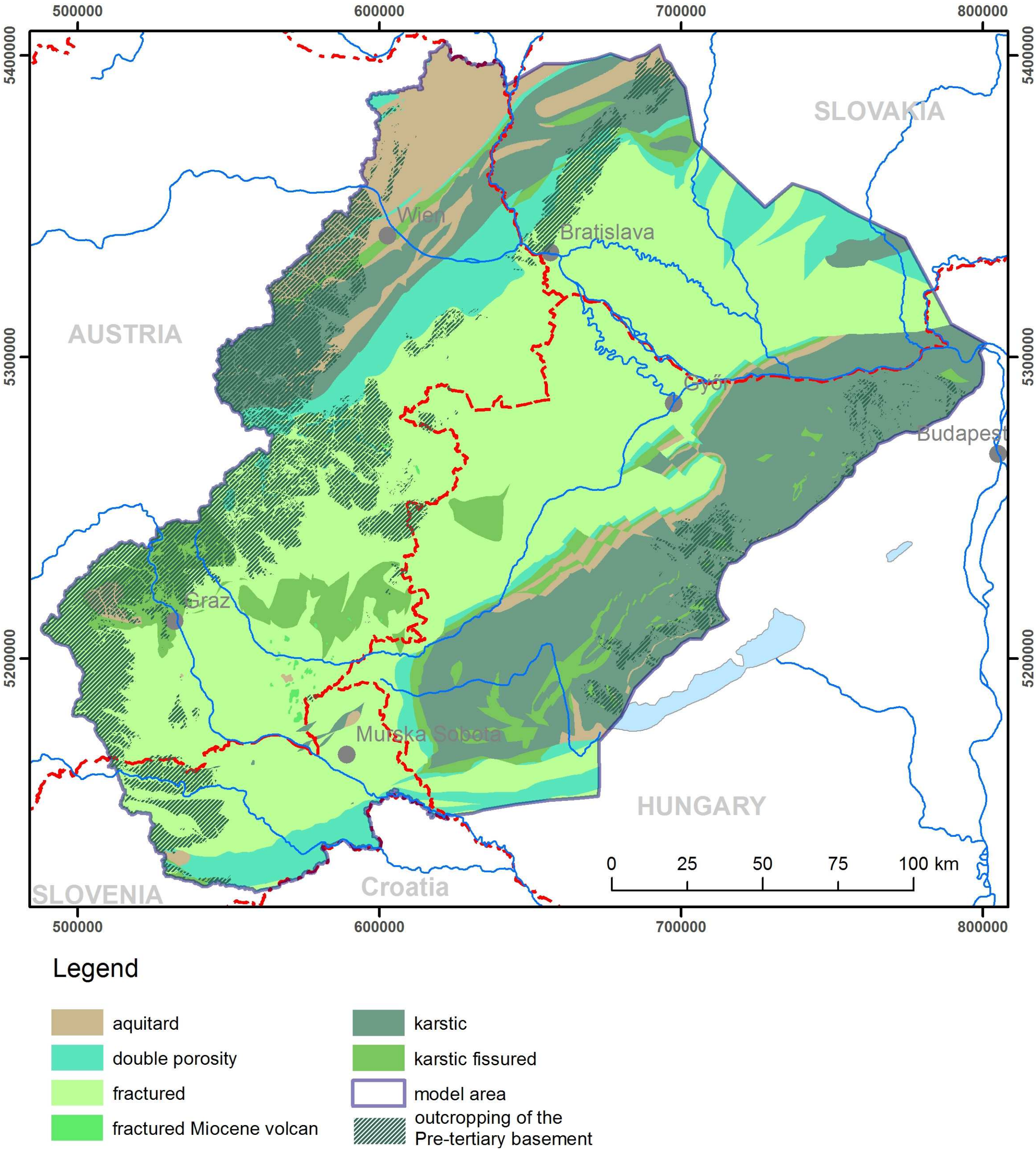

Figure 32: Hydrogeological categories of the basement formations

5.2.3.Boundary conditions

5.2.3.1.Recharge

In the basement model the most important element of recharge is the infiltration from precipitation, too. Contrary to the porous model, recharge areas are restricted to small regions where the basement formations are outcropping to the surface. Recharge values are determined with the combination of the hydrogeological characterization of the surface geological formations and meteorological data, the same way as in the porous model.

Recharge in karst aquifers can determined from the annual precipitation as well. This method was developed upon long time series of spring yield measurements and precipitation data of Aggtelek region in Hungary (Maucha 1990).

5.2.3.2.Discharge

In natural condition the discharge area of the basement model is represented by the spring areas. Usually these are warm springs, located at the margin of the mountain regions. The host rock formations of the springs are different, but mostly they are Triassic limestones and dolomites. The location of springs is shown on Figure Figure 33.

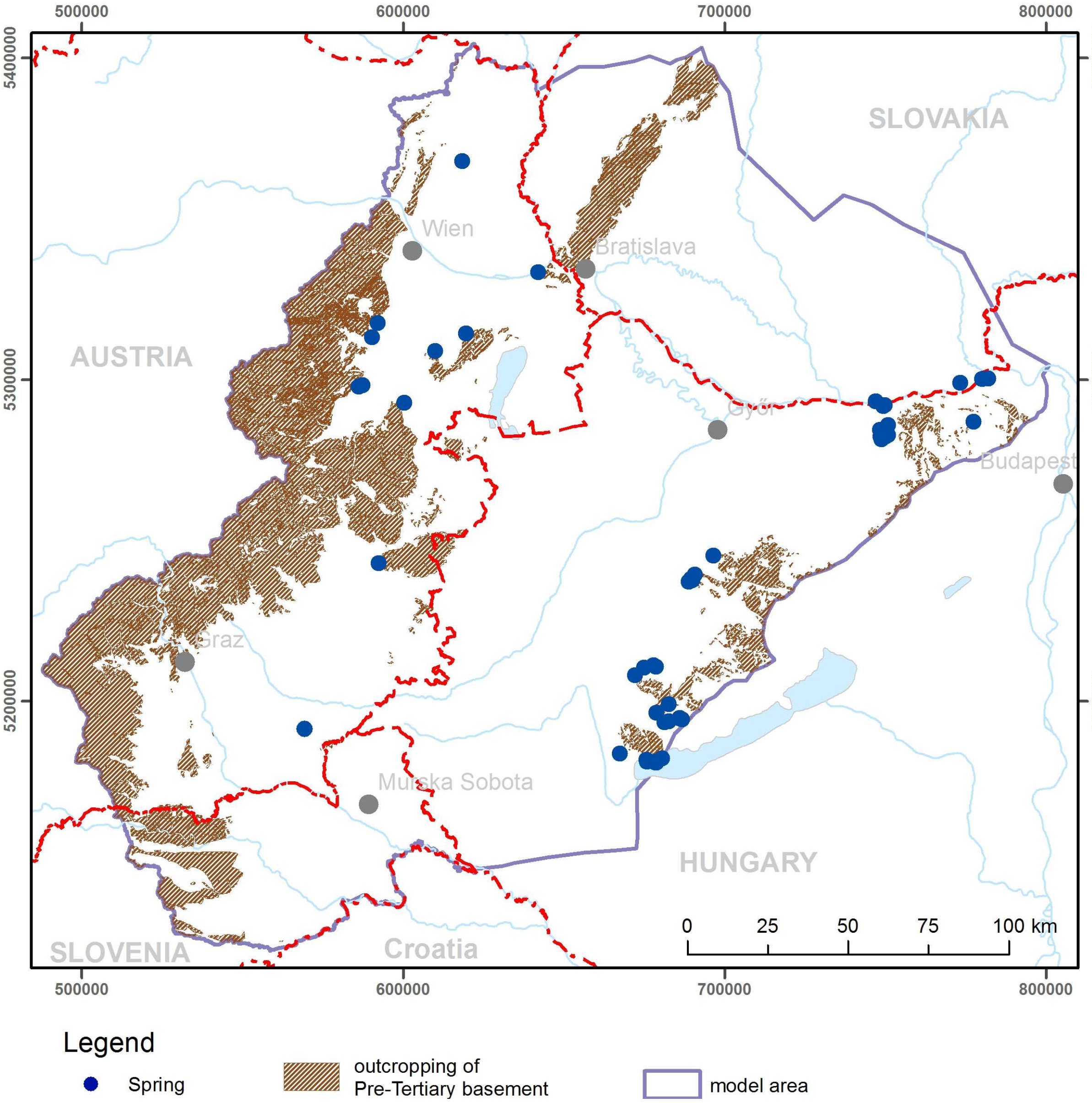

Figure 33: Discharge areas of the basement flow system

5.2.4.Calibration targets

There are only a few monitoring well hitting the basement formations. Similarly to the porous model their average time series of karstwater heads of the last two decades were used for calibration.

In the calibration process of the basement model, the other calibration elements got greater importance. The yield of the spring was controlled in everywhere (Figure 34). The hydrogeochemical characters were also evaluated, they may indicate lower speed of groundwater flow and stagnant water, or contrary the fresh water refer to good and fast conection to the recharge area. The age of water based on isotope measurements was checked with simulating the flow pathlines.

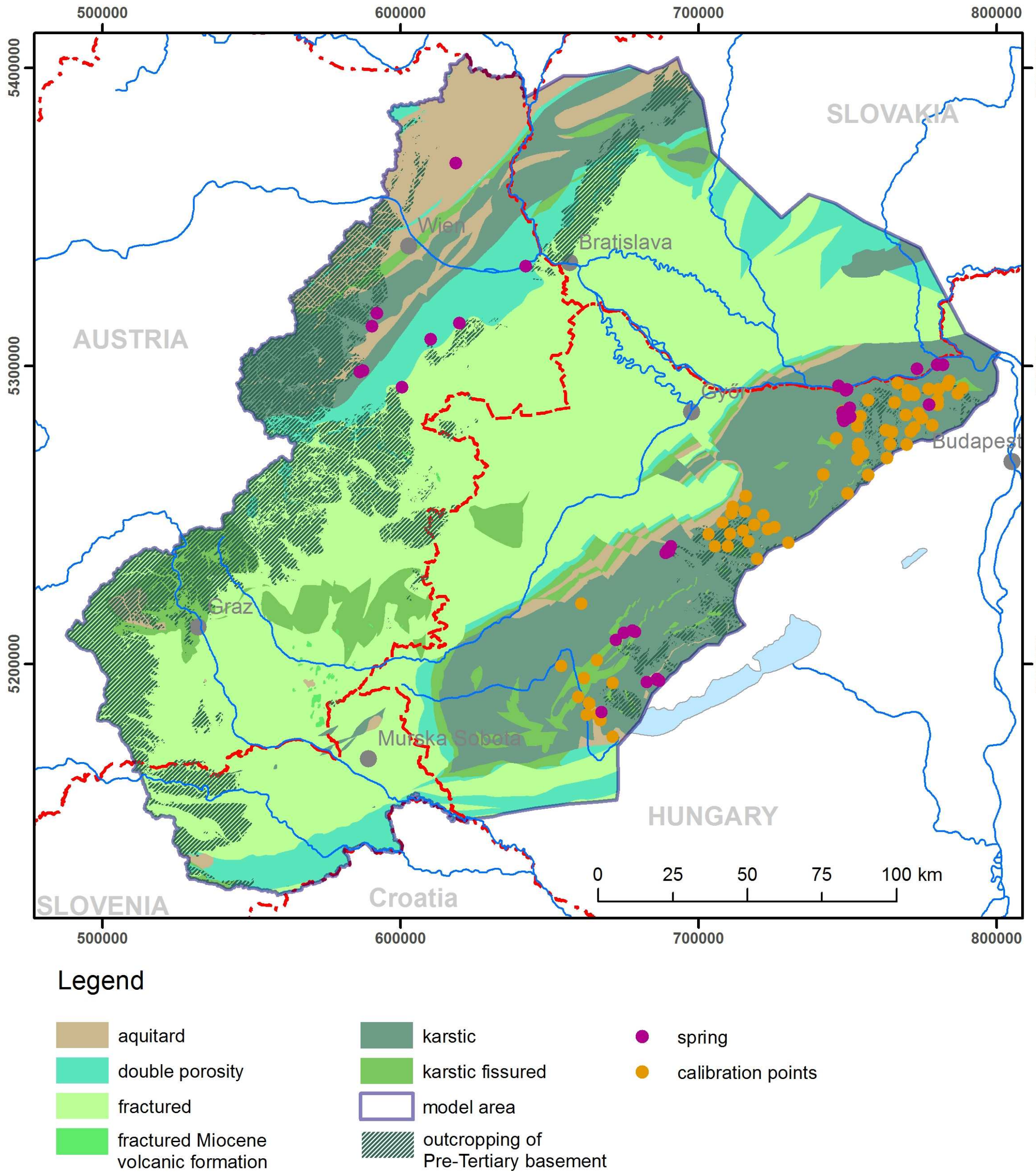

Figure 34. Elements for calibration of the basement model

The basement model is calibrated the same way as the porous model. Calibration was taken at different parts of the model area (Figure 35-37).

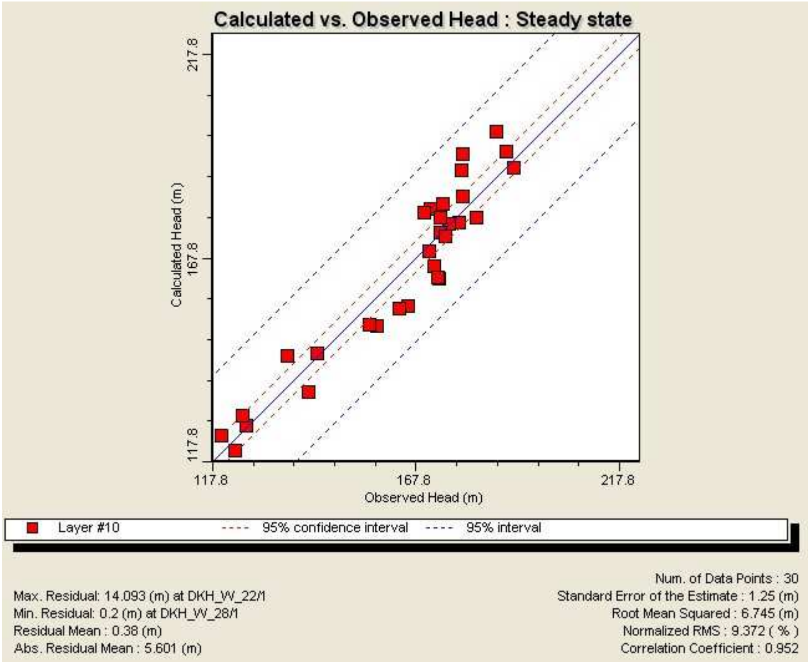

Figure 35. Calibration of karst water level in the western part of the Transdanubian Midmountains

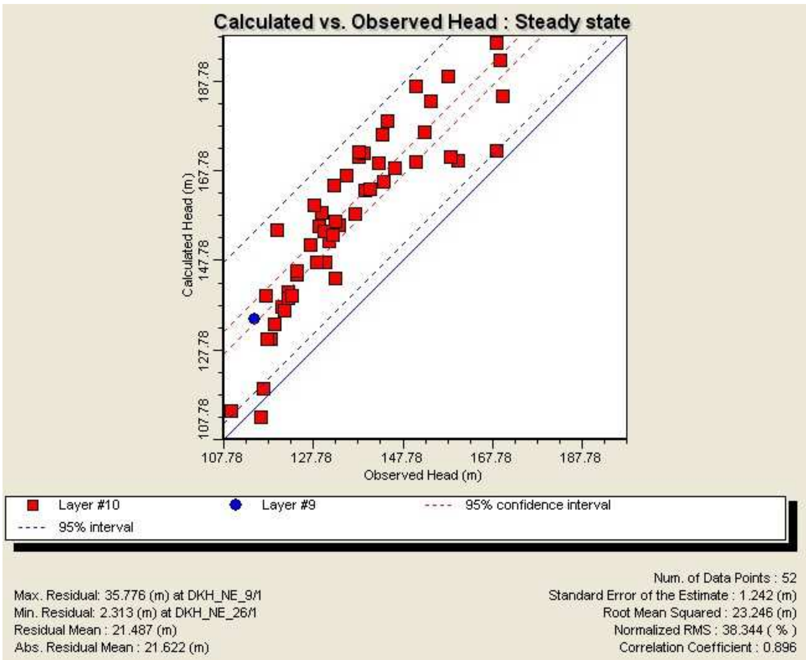

Figure 36. Calibration of karst water level in the NE part of the Transdanubian Midmountains

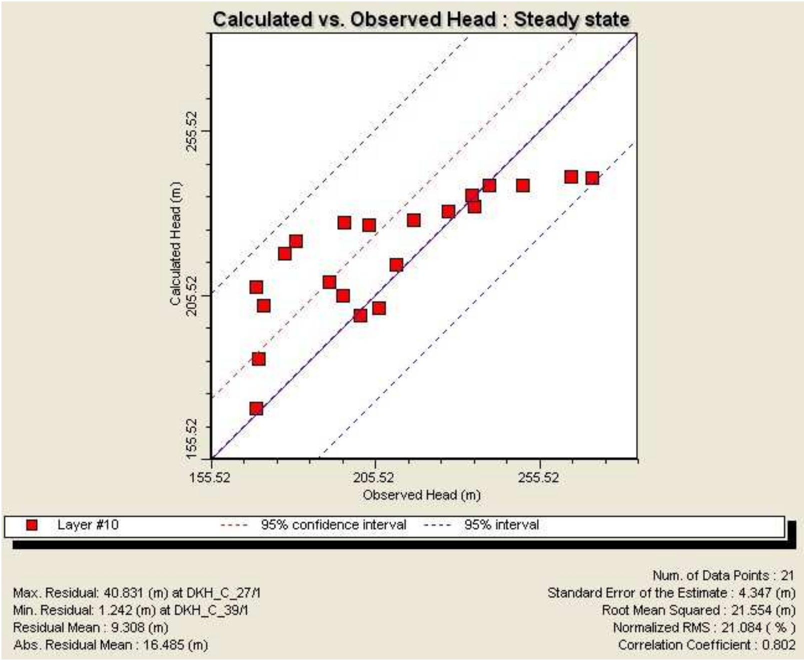

Figure 37: Calibration of karst water level I the central part of the Transdanubian Midmountains

5.3. Merging of the porous and basement models

Having the same model grid the physical merging of the two models was a simple task adding the basement layer to the porous model.

However when merging the two models, the new hydrostratigraphical units have to be determined in the new model. The lower Pannonian and Miocene formations separate the two hydraulic systems. They did not have any role in the previous separate models, but had to fixed in the merged model. The Lower Pannonian formations represent one, the Miocene formations represent three model layers. Similar to the other models their conductivity values were given according the hydrogeological characterization of the geological formations.

All the applied boundary conditions and calibration elements were used in the merged model.

5.4. Output of the model

The major outputs of the Supra Regional model are the following:

- computed shallow groundwater table, confined cold and thermal water heads in the porous parts, karst and fissured water table and thermal karst water heads;
- computed flow lines, groundwater velocities and directions in 3D
- computed discharge at the major springs and at other discharge objects (rivers, seepage faces);
- computed and aggregated drawdown of the production wells;
- computed budgets of the major delineated groundwater bodies, including trans-boundary water transfers.

5.4.1.Groundwater table map

The modeled groundwater table (Figure 38) also provides information for the surroundings of the administrative area of the project, and highlights the role of those neighboring areas in the recharge and discharge processes.

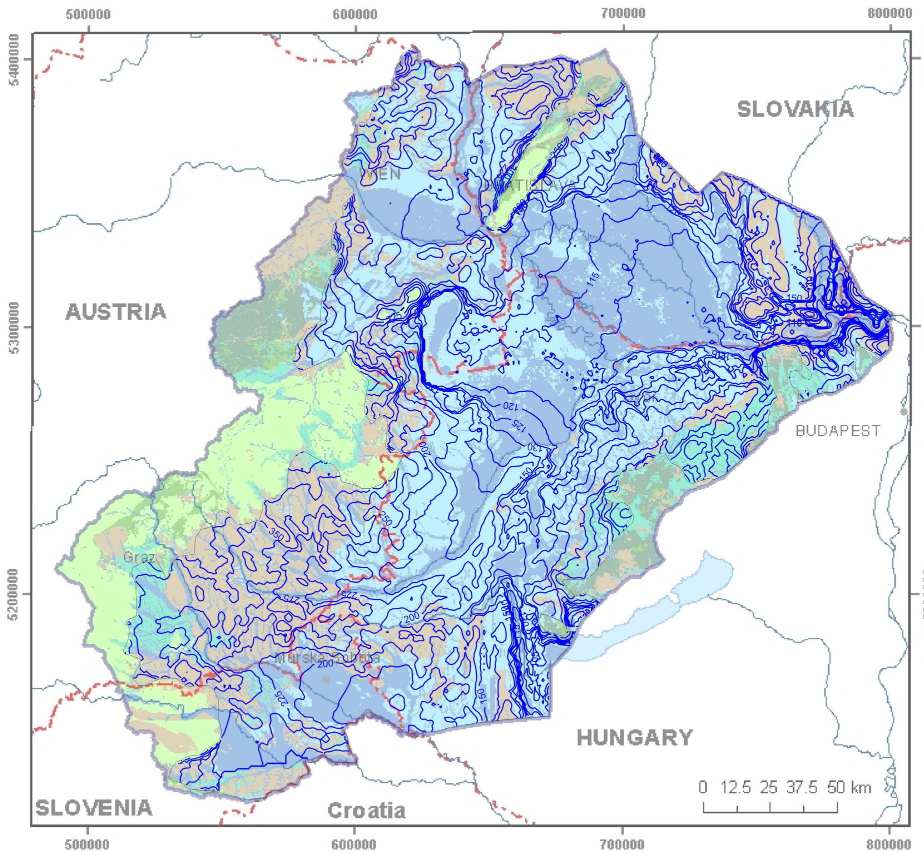

Figure 38: Calculated groundwater table

5.4.2.Hydraulic potentials (heads) in 3D

Figure 39-Figure 41 give information on the 3D pattern of the hydraulic potential fields and through this way the 3D flow patterns as well (flow directions are perpendicular to the potential field from higher to lower head values).

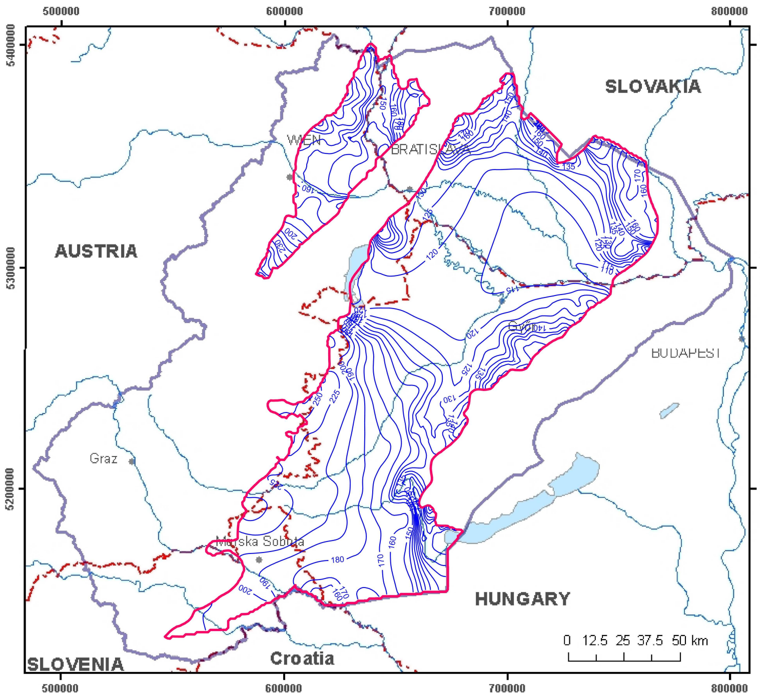

Figure 39: Head values in the cold water aquifer layer of the Upper Pannonian (Model layer 3)

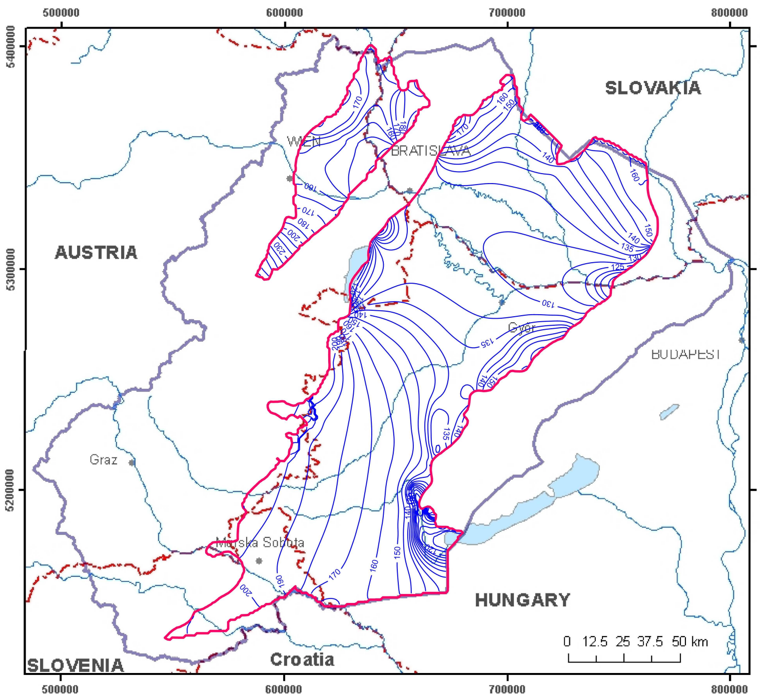

Figure 40: Head values in the thermal water aquifer komplex of the Upper Pannonian (Model layer 6)

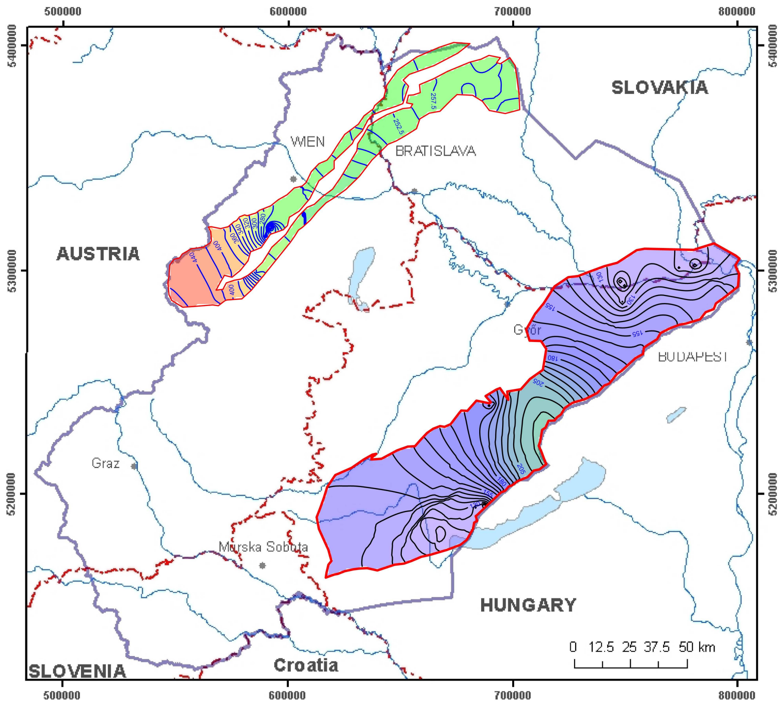

Figure 41: Head values in the karst aquifers of the basement (Model layer 10)

5.4.3.Budgets of the transboundary thermal groundwater zones

It is clearly shown that the major thermal water flows through the national borders. The budget of these transboundary zones are calculated for the supra-regional model (Table 3. It demonstrates the possible water transfers between the cold and thermal groundwater bodies. It also gives information on the trans-boundary budgets. Similar tables can be produced for the present state abstractions, or any reasonable scenarios. The supra-model can be used this way also for the trans-boundary management purpose.

Table 3. Zone budget of the transboundary areas (values are in m^3/d)

From \ To	Cold unconfined (14)	AT Cold confined Pa2 (11)	AT thermal Pa2 (10)	SK Cold confined Pa2 (7)	SK thermal Pa2 (6)	SLO Cold confined Pa2 (8)	SLO thermal Pa2 (12)	HU Cold confined Pa2 (4)	HU thermal Pa2 (5)
Cold unconfined (14)		**24180**		**63250**		**15330**		**101410**	
AT Cold confined Pa2 (11)	**10840**		**1570**	**390**	**2**	**910**		**22320**	**390**
AT thermal Pa2 (10)		**2480**						**60**	**1960**
SK Cold confined Pa2 (7)	**73620**	**150**			**16960**			**610**	**100**
SK thermal Pa2 (6)	**180**			**20510**				**130**	**8560**
SLO Cold confined Pa2 (8)	**14540**	**460**					**11690**	**9800**	**440**
SLO thermal Pa2 (12)						**8360**			**6650**
HU Cold confined Pa2 (4)	**144660**	**6570**	**90**	**3410**	**60**	**9170**	**1**		**30470**
HU thermal Pa2 (5)	**330**	**170**	**2690**	**170**	**2560**	**550**	**2720**	**36700**	

5.4.4. Modelled drawdown effects

Figures Figure 42-Figure 47demonstrate the trans-boundary effects of the thermal wells' productions. All of them show the drawdown in meters caused by the production of thermal wells, at the 6th model layer. This layer contains of the Upper Miocene delta front, delta plain sandstone aquifers, in the western Pannonian region.

Figure 44-Figure 47 shows separately the drawdown effects of the thermal water productions in N-Hungary, S-Hungary, Slovakia and Slovenia respectively. These figures clearly demonstrate, that the production in each region has trans-boundary consequences.

The computed drawdowns of all productions of second half of the last decade are shown in Figure 42. The regional values are rarely larger than 8 m, mainly in the Slovenian part and around the Zalakaros spa (SW-Hungary).

One of the more realistic scenario is supposing 5 times higher production at each present utilization area in the future (next decade). New developments are typical installed at the areas where the infrastructures are developed, near to well known spas with traditions. According to this scenario (Figure 43) the regional drawdown is larger than 20-30 meters. It means the depressions would be much larger at the given production wells (>50-100 m). Further production at these sites would require too much energy (pumping) there their economic feasibility could be questioned. This means that this „5 times higher production without re-injection" scenario should have been avoided.

Scenario analysis can significantly contribute to management solutions/ recommendations: the maximum allowable production rates (e.g. the maximum allowable drawdown at every existing production well) should be determined, then their accumulated effect should be computed. Then based on the same models, the maximum allowed hydraulic potential level should be computed at some representative, or planned monitoring sites. The next step is determining the reversal point (value) of the time series of these monitoring wells, together with formulating the required measures (e.g. decreasing the productions at a certain percentage at each, or selected sites.)

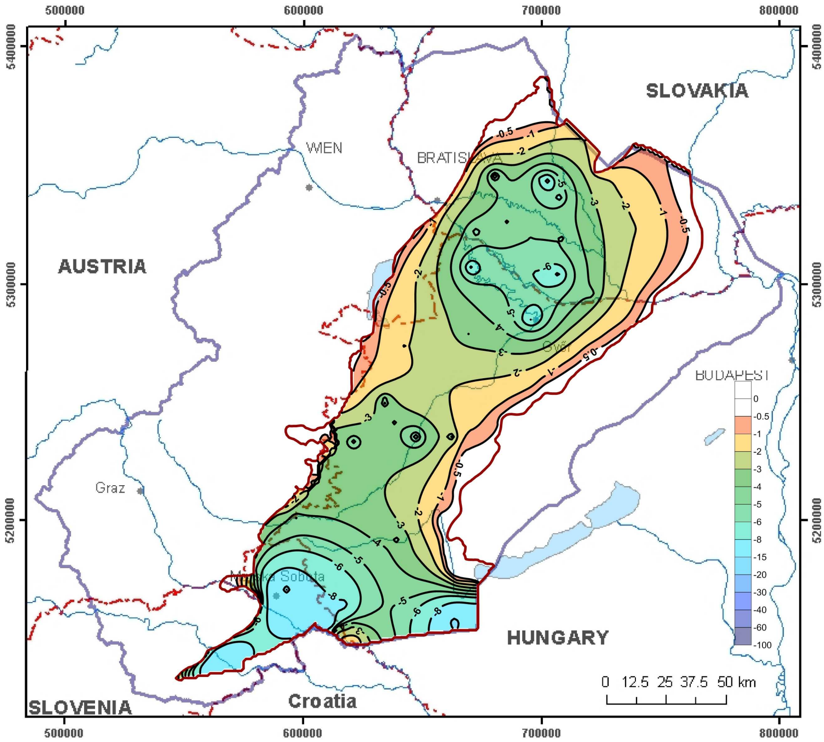

Figure 42: Computed drawdown effects of the cummulative production of all thermal wells

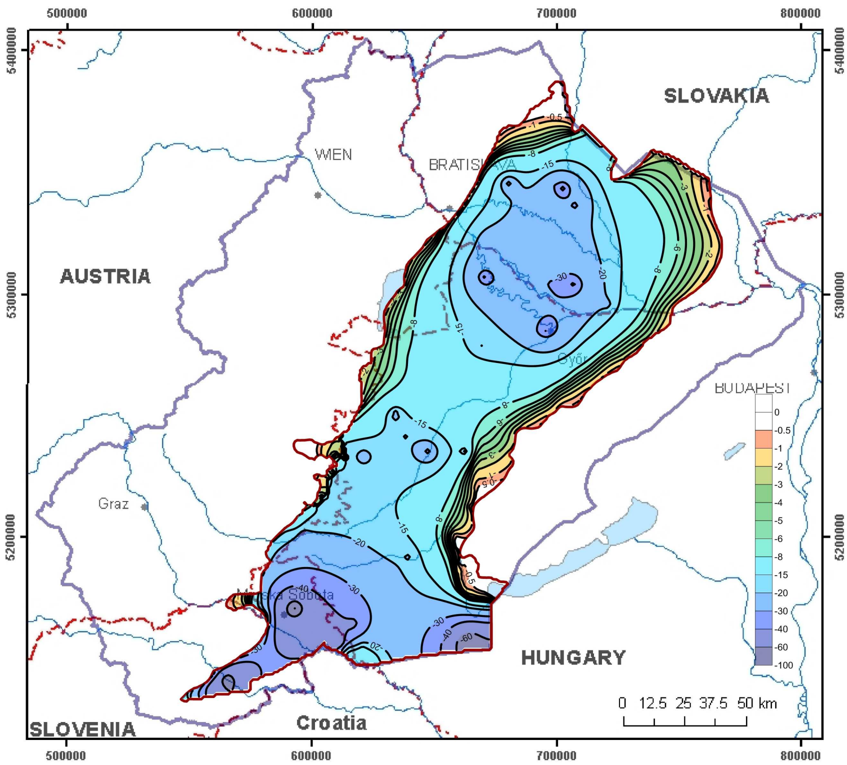

Figure 43: Computed drawdown effects of the cummulative production of all thermal wells assuming 5 times higer production rates

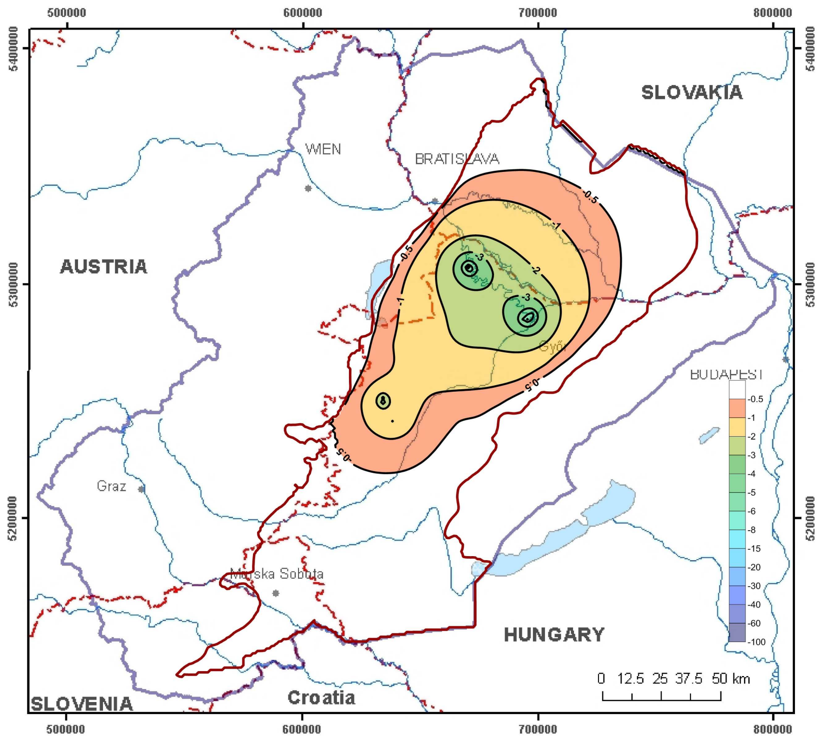

Figure 44: Computed drawdown effects of the cummulative production of all thermal wells in N-Hungary

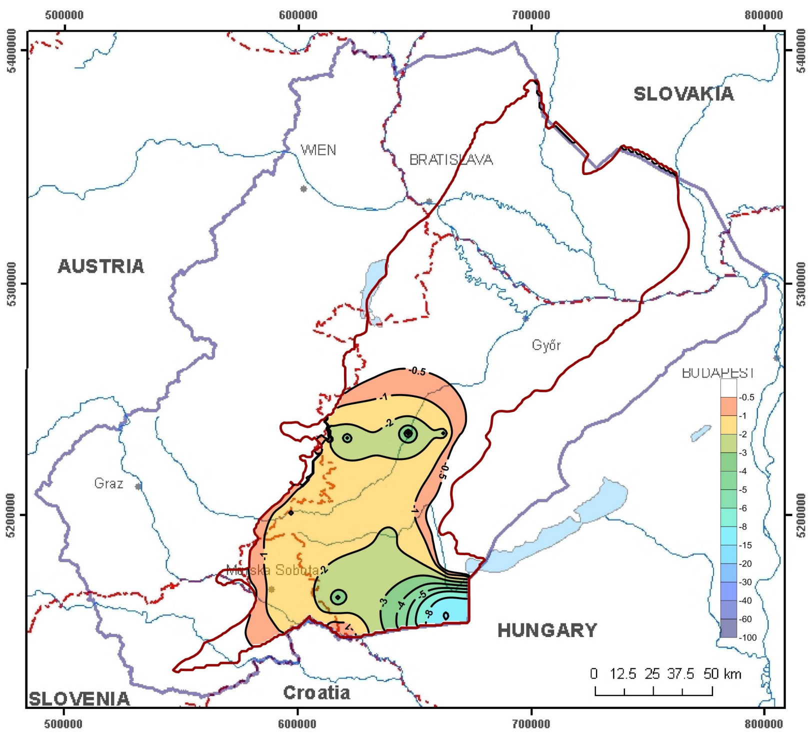

Figure 45: Computed drawdown effects of the cummulative production of all thermal wells in _S-Hungary

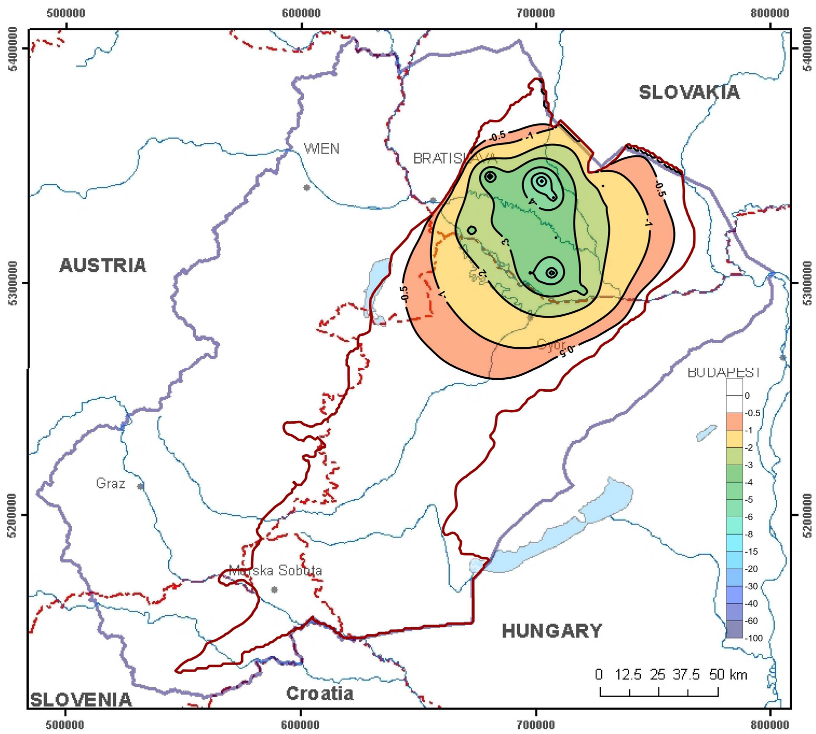

Fig. 51

Figure 46: Computed drawdown effects of the cummulative production of all thermal wells in Slovakia

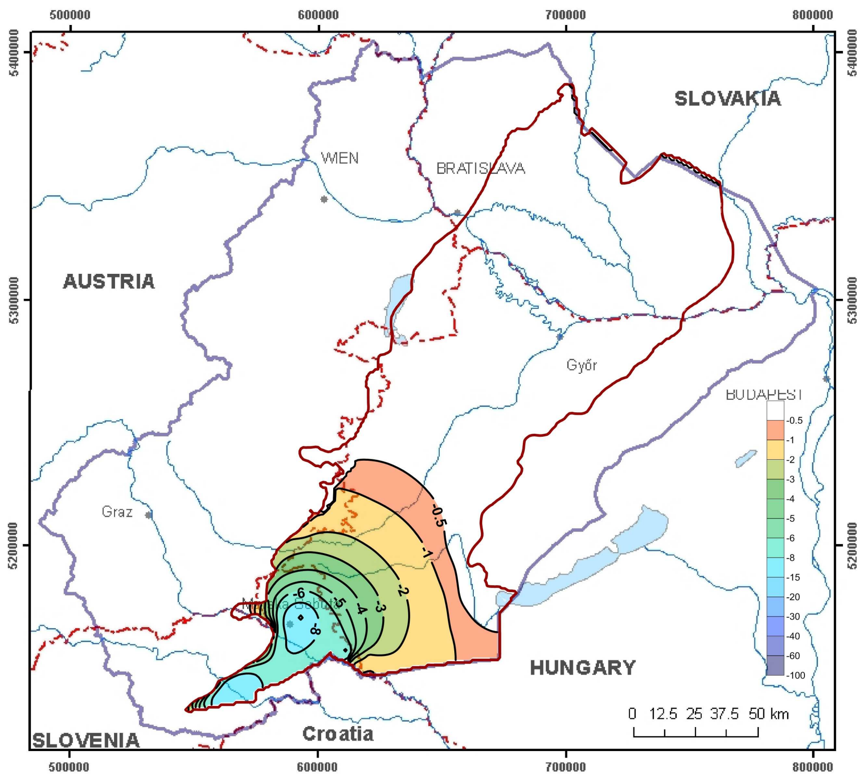

Figure 47: Computed drawdown effects of the cummulative production of all thermal wells in Slovenia

6.Results of the supra-regional hydrogeological model

The supra-regional model is a unique hydrogeological flow model both in scale and regarding its the transboundary character. It is based on a special theory of combining the upper porous and the lower basement model of the fractured-karstified formations.

The most important result of the supra-regional hydrogeological model is providing an overview on the hydrogeological thermal water flow systems of the entire TRANSENERGY project area. The relation between the main thermal water regimes was determined. The calibrated model was used to calculate the groundwater budget components of the delineated cold groundwater and thermal water bodies across the different parts of the country borders. Furthermore, the supra-regional model will serve as a basis for the pilot models. The model is ready:

1. for scenario evaluations, modeling the drawdown (depression effects) of different production states jointly evaluated by the experts of the partner countries,as an important input for the management recommendations;

2. for hydrogeochemical and isotope-hydrological evaluations by its quantitative information on the flow systems, like flow-lines, velocities, budgets, and vice versa: the model is ready for developing the age and detailed mixing information of the region: connection to the hydrogeochemical studies;

3. for the coupled flow and transport models, especially for the regional pure convective and density (buoyancy) driven heat transport system: connection to the geothermal evaluations;

4. for the construction of the pilot study areas, by providing them concept, prior parameters, boundary conditions and formulating questions raised on during supra modeling

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