3.17. SOUTERN DOBROGEA

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Geological and structural framework

The Southern Dobrogea represents a sector of Moesian Platform delimited by major faults Capidava-Ovidiu, to the north and Intra-Moesian (Călăraşi-Fierbinţi-Sabla), to the south, by Danube River to the west and Black Sea to the east. This region covers a surface about 5000 km^2.

Above the Archean and Proterozoic crystalline bedrock it follows, discordantly, sedimentary deposits belonging to Paleozoic, Mesozoic and Neozoic sedimentary cycles.

The Paleozoic formations comprise marine deposits (sandstone, clay and limestone) of Silurian – yearly Carboniferous age and continental deposits (clay, sandstone, breccias) from medium Carboniferous – yearly Permian period. The formations are in discordant sequence and the structure is a homocline sloping southward.

The Mesozoic and Neozoic formations, widely developed in the area, comprise several sedimentary cycles separated by almost horizontal discordances (Zamfirescu et al, 1994). From lithological point of view there are: *(a)* terrigenous carbonate sediments, formed in paralic environment, with up to 100 m thickness (Triassic - lower Jurassic); *(b)* carbonate complex (Oxfordian - Barremian), 400-1200 m thick, widely developed on the entire Southern Dobrogea area (except the

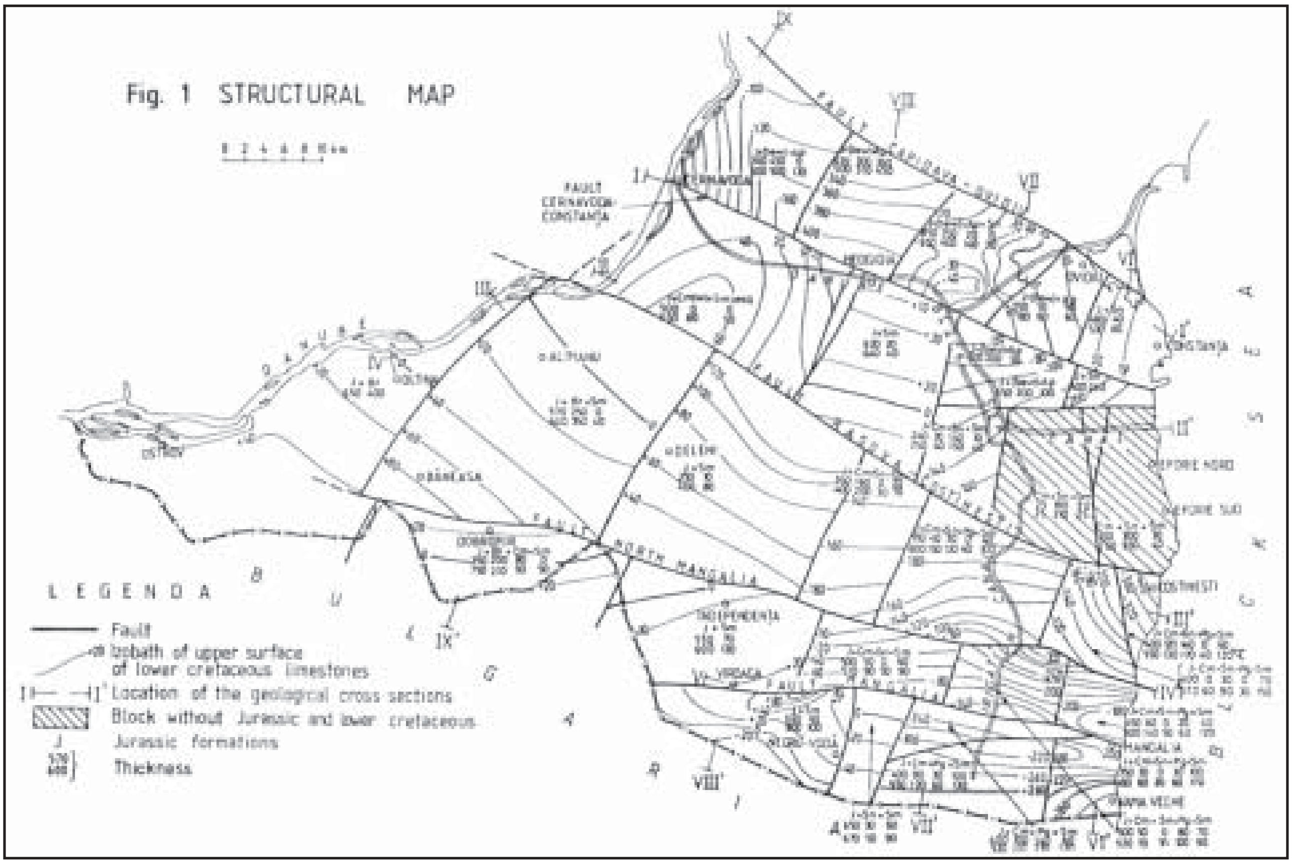

Figure 1. Structural Map of Southern Dobrogea.

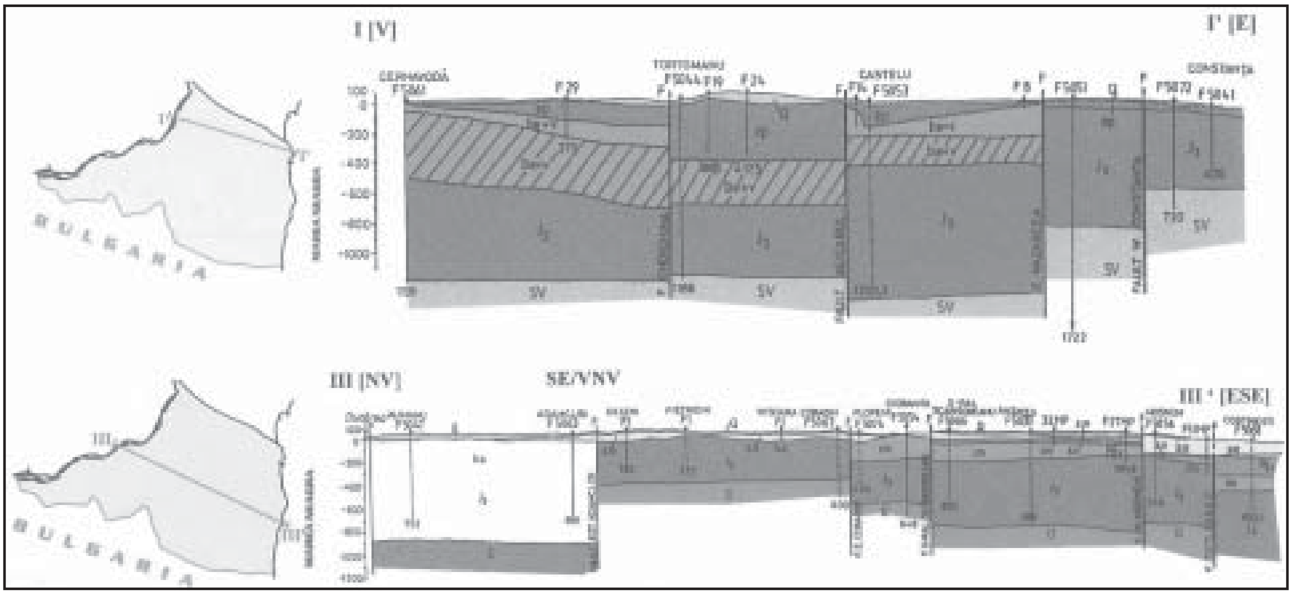

Figure 2. Geological cross-sections.

Lazu-Straja-Topraisar-Tuzla tectonic block), comprising limestone alternating with dolomite, sandy limestone, marl and clay, locally highly fissurated and carstified; in the northern part, between Capidava-Ovidiu and Cernavoda-Constanţa faults, the upper part of this complex has an evaporitic facies, 100-400 m thick, represented by clay, marl, calcareous sandstone and gypsum; *(c)* continental deposits, belonging to Aptian, Albian or Cenomanian cycle, represented by sand, sandstone, conglomerate, glauconitic sand, sandy limestone; *(d)* chalk and sandy limestone of Senonian age; *(e)* limestone and numulitic sand of Eocene age; *(f)* shelly and oolitic limestone, clay and sand of Sarmatian age. All over the Southern Dobrogea area there is a loess deposit cover.

The heterogeneous spatial distribution of Mesozoic formations together with facies great variation suggest a sedimentation process in a tectonically active area, broken up in blocks having different position (covered/uncovered) during the geological evolution.

The blocks movements, limited by faults almost vertical, were developed in several successive moments, during the Cretaceous and Paleogene diastrophic phases. Consequently the position of different limits varies from one block to other. The structural map, presented in Fig. 1, shows: the blocks are separated by two fault systems oriented WNW-SSE and NNW-SSW; the first type faults, parallel with Capidava-Ovidiu major fault, were more active, having also horizontal displacement; the crystalline bedrock is steeply plunging westward (to the Danube River), leading to a significant increase of carbonate complex thickness (over 1000 m), is going up toward NE (north Constanţa area) and plunging to S and E (on the coast area) – see Figure 2 (more geological cross sections are available in the paper Zamfirescu et al, 2005).

The J3-K1 carbonated complex is developing at the scale of the entire Moesian Platform, with a tectonic structure similar to Southern Dobrogea. The thickness of this stratigraphic unit varies from 700 to 1600 m (in the Bucharest city area and northward) but decrease to 100-300 m at Giurgiu, near the Danube River (where is incomplete). The formations are steeply dipping to north (by faults). The lower Cretaceous is outcropping in several places: on the right bank of Danube, upstream to Ruse, between Ostrov and Cernavodă and also along the valleys flowing northward to Danube, on Bulgaria and Romania territory.

The lower (deep) aquifer

In the upper Jurassic - lower Cretaceous carbonate complex is developing a regional aquifer system, at the scale of entire Moesian Platform. The conceptual model presented in the Figure 3 allows the following observations:

- On Romanian territory the main flow direction is W-E. The discharge into Black Sea takes place especially in the Constanţa town area, through the blocks delimited by Capidava-Ovidiu and Cernavodă-Constanţa faults (Mamaia Lake area).

- The main recharge zone is on Bulgarian territory. Between Giurgiu and Cernavodă there is a complex hydraulic relationship aquifer – Danube River.
- In Romania, on a 20-30 km wide band located along Danube River, the total mineralization is less than 1 g/l and temperature around 15-16°C. Northern to Bucharest and in the western part of Bulgaria the aquifer is steeply plunging up to 3000 m. Temperature could be over 70°C while the total mineralization exceed 3 g/l.
- The temperature profiles recorded in wells northern to Bucharest, where the thickness of carbonate complex exceeds 1000 m, reveal the presence of closed convection cells. The water movement is possible due to difference between vertical component of pressure gradient and fluid phase density. Thus, through reservoir the flowrate has significant values but the dynamic resource is of less importance.

In Southern Dobrogea the permeability of tectonic blocks for J_3-K_1 complex express the geological evolution of each block, being less influenced by actual groundwater dynamics.

The transmissivity values for the aquifer range from tens or hundreds m^2/day to more than 150.000 m^2/day. The hydraulic gradients are, usually, less than 0.05%. The hydraulic conductivity is usually greater than 10^2 m^2/day and storage coefficient range between 10^{-3} - 10^{-4}.

The piezometric map of the deep aquifer *(Figure 4)*, for the years 1988-1989 lead to the following comments:

- The J_3-K_1 carbonate complex represents an aquifer system with unitary piezometry at the Southern Dobrogea scale. The flow net distortions are related, without exceptions, to changes in permeability and thickness of carbonate formations at the blocks contact.
- The main flow direction is S-N and became W-E close to Capidava-Ovidiu fault and within Costineşti-Mangalia block. The natural drainage center is represented by Black Sea through

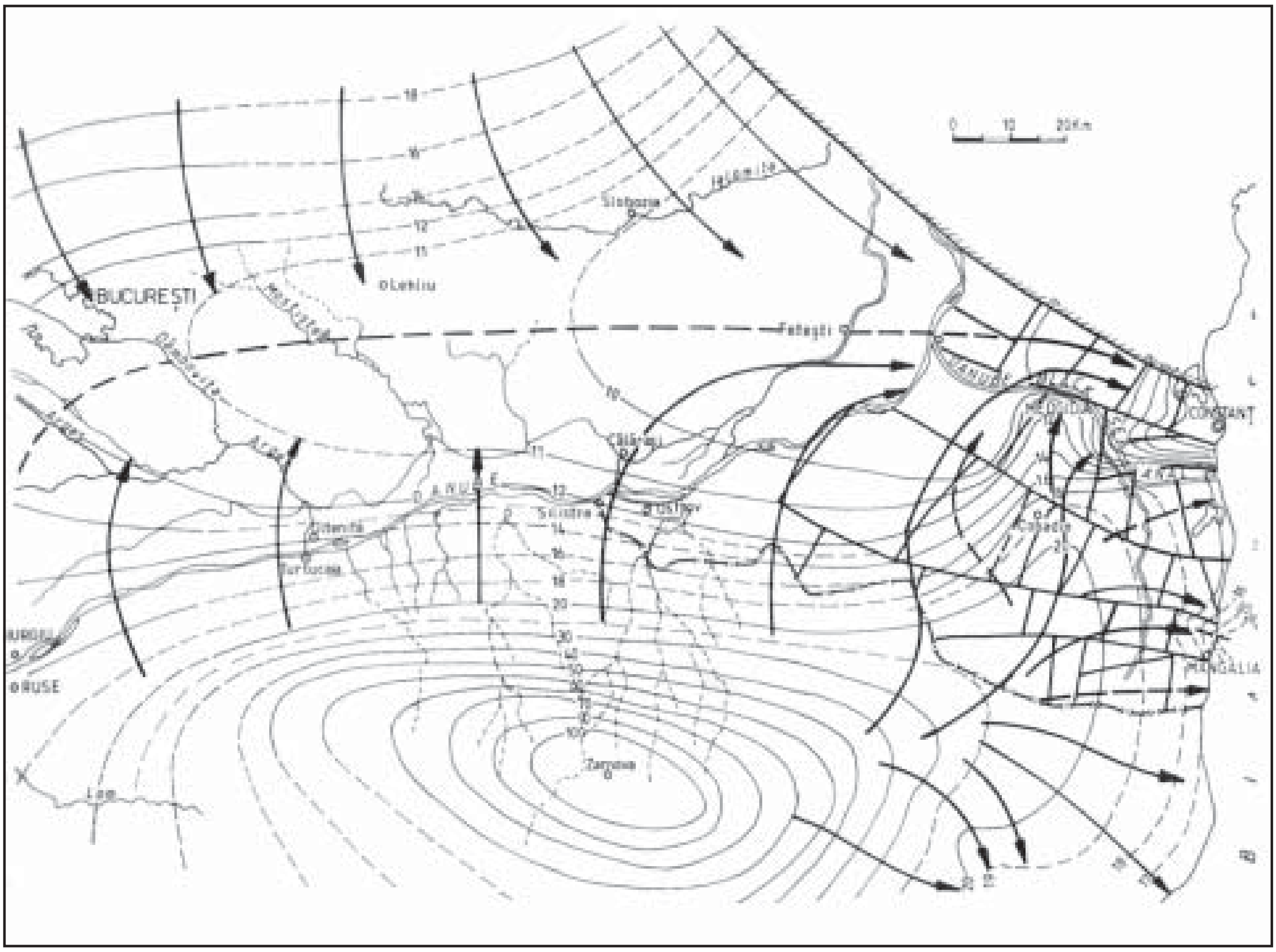

Figure 3. Regional hydrodynamic conditions for deep aquifer. Conceptual model.

Mamaia Lake (mainly) and swamp area northern of Mangalia (secondly). The recharge of the aquifer system is made from S, W and SW.

- The aquifer is confined on about 60% of Southern Dobrogea surface. In the western part and southern of Cernavodă town there is an area with unconfined conditions. There the aquifer can be directly influenced by precipitation regime, infiltration from irrigation systems and leakage from upper aquifer.
- There is a direct connection between specific yield of the wells and the equivalent transmissivity of the tectonic blocks. Thus, specific yields less than 1 l/s·m relate to transmissivities of tens to hundreds m^2/day while specific yields greater than 80 l/ s·m relate to transmissivities greater than 100,000 m^2/day.

The total mineralization of groundwater usually ranges between 300 and 1000 mg/l and the total hardness is 8-26 germane degrees. The water is bicarbonate, calcium-magnesium type with temperature of 20-26°C.

The upper (shallow) aquifer

In the eastern half and southern part of the South Dobrogea the Sarmatian limestone is forming a plate with thickness up to 300 m. There is developing an unconfined aquifer that represent the main water supply source for the coastal area southern to Eforie town. The development of this aquifer is controlled by the existence of Senonian chalk as impervious bed. To the S and SE the Sarmatian and Eocene permeable formations are forming a unitary aquifer.

By analyzing the piezometry for the 1988-1989 period (comparing with 1972 year) are resulting the following (see Figure 5):

- The unconfined Sarmatian (and Eocene) aquifer, is recharged from precipitation and from

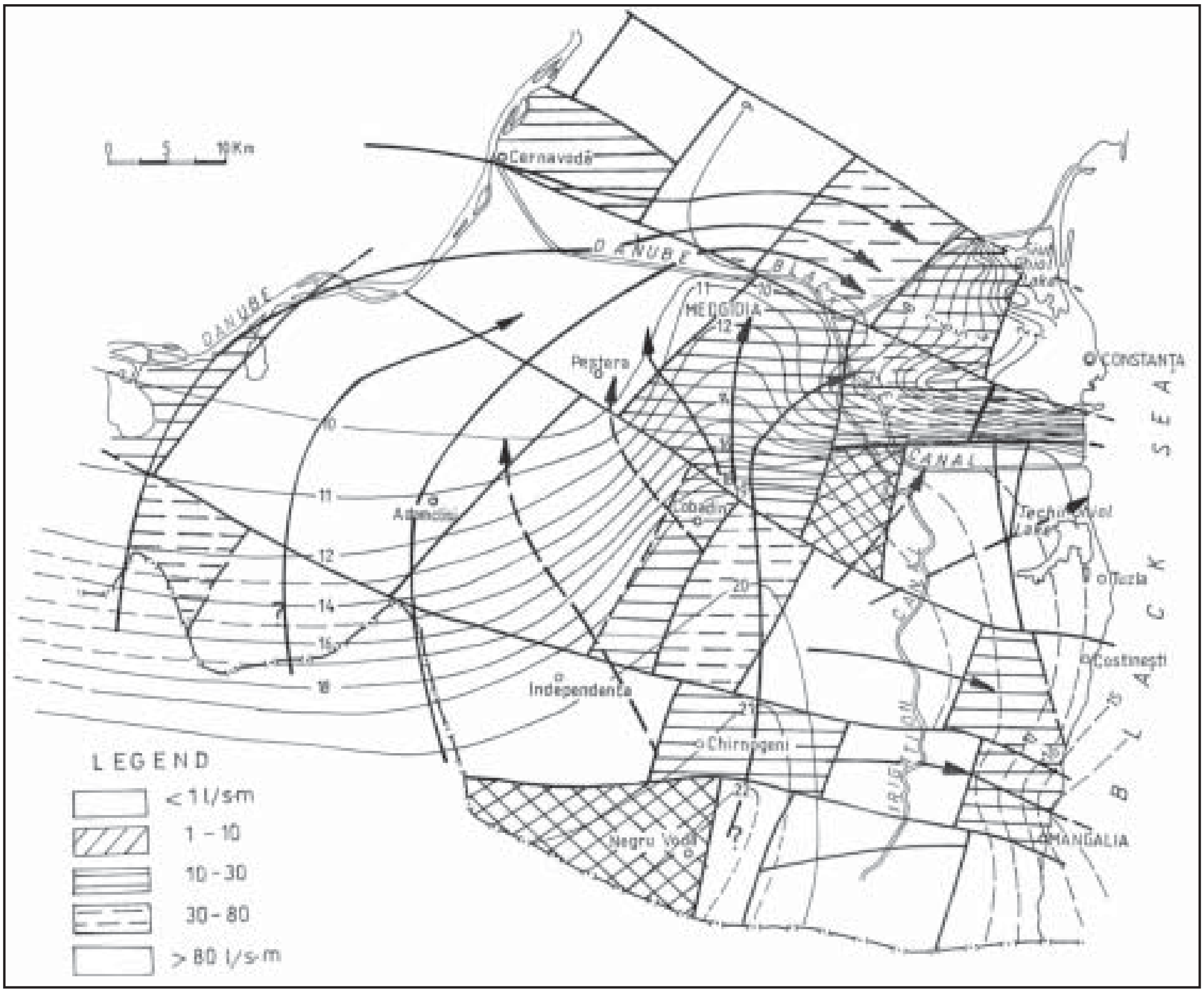

Figure 4. Piezometric map of deep aquifer with distribution of specific yield.

the diffuse losses from irrigation systems;

- The main drainage area is Black Sea through the lake system along the coast, southern to Constanţa town;
- After the completion of Carasu irrigation system (1972), the water table rise more than 50 m, with different consequences: increase of discharge to littoral lakes (hydrologic and hydrodynamic impact on Techirghiol Lake); increase of recharge, by leakage, of the deep aquifer; increase of discharge flowrate on valleys;
- The hydrogeological parameters are: hydraulic gradient from 0.9% (Techiorghiol Lake area) to 0.14% (to the south); transmissivity of 50-2000 m^2/day, with local values of 5000 m^2/day.

A W-E hydrogeological cross-section (Figure 6) shows the relationships between the two superposed aquifers:

- In the western half part of the Southern Dobrogea there is a single, phreatic aquifer;
- Senonian chalk and the Cenomanian sand behave like an aquitard, separating hydrodynamically the two aquifers;

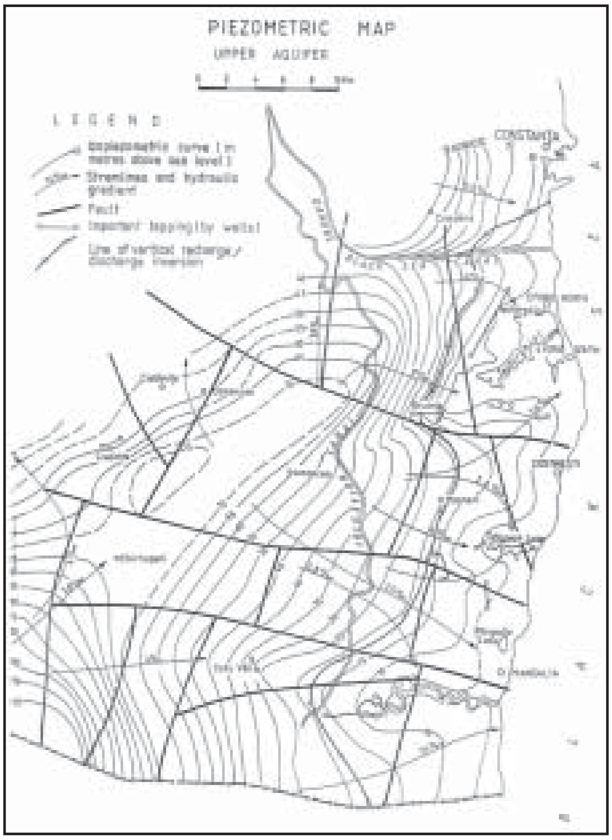

Figure 5. Piezometric map of upper (shallow) aquifer (1988-1989).

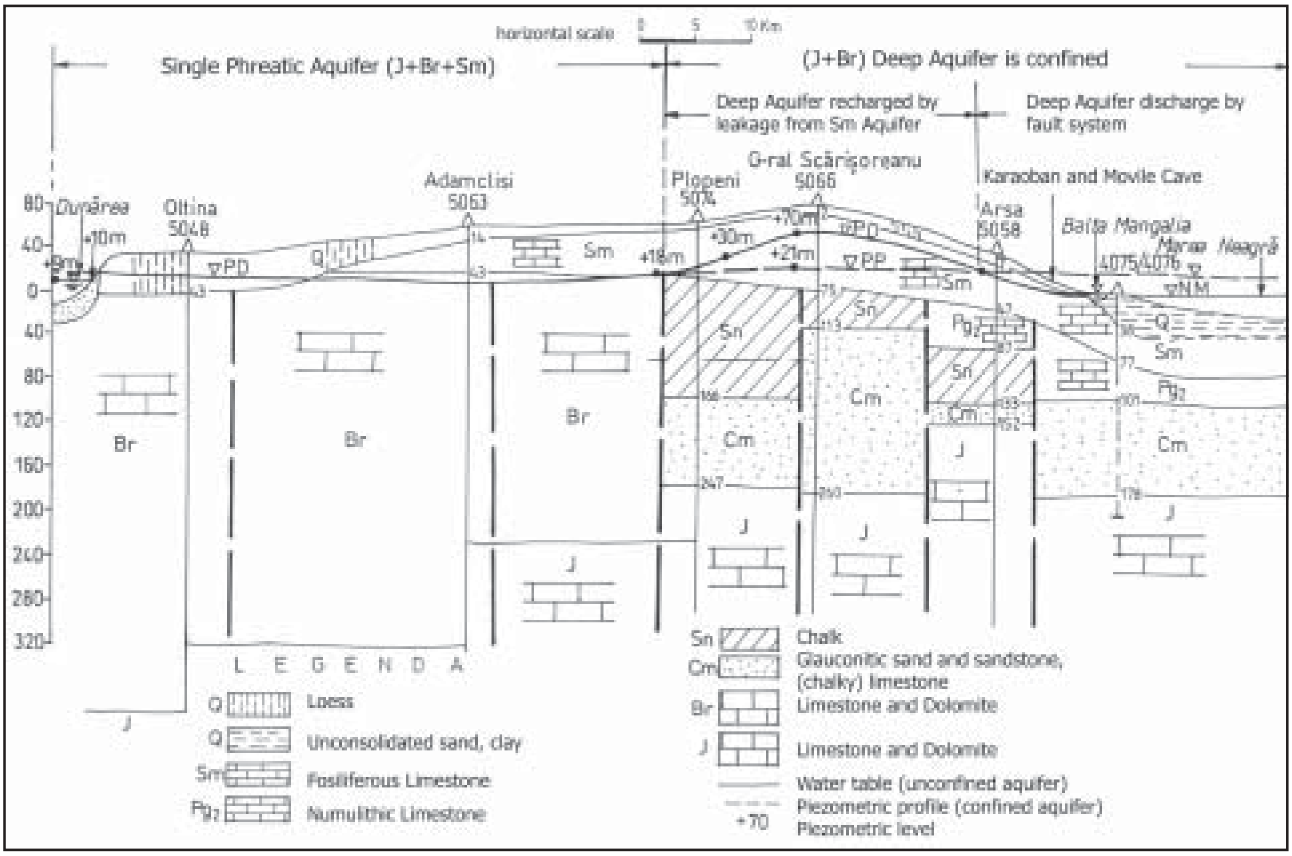

Figure 6. Sinthetic hydrogeological cross-section. Relationship between aquifers in Southern Dobrogea.

- The spectacular rise of the water table of the upper, phreatic aquifer, due to water losses from the irrigation system (after 1972), determined an increase of the leakage to the lower aquifer;
- The upper, phreatic aquifer is discharging directly to the Black Sea. The lower, confined aquifer flows also to the Black Sea but through faults, keeping the hydraulic head greater than sea level for 1-2 km offshore. Consequently, in the coast area there is a 5-10 km wide land strip where the relationship between the aquifers is reversed – see the line of vertical recharge/discharge inversion on Figure 5. The springs occurring along the seaside represents a mixed groundwater from the upper aquifer and from deeper aquifer, by fault planes.

The Figure 7 shows an attempt to correlate our piezometric map from Figure 5 with that published by Bulgarian hydrogeologists (Pulido Bosh et al, 1996) concerning the southern part of the Sarmatian limestone aquifer. It results the following:

- There is a hydrodynamic continuity of the upper aquifer from Romania to Bulgaria. The southern recharge component has less weight from quantitative point of view.
- Through the valleys from the southwestern corner of South Dobrogea, where outcrops the K1 limestone, the upper aquifer from Bulgaria is discharging into the Romanian deep aquifer (in the area with unconfined regime).

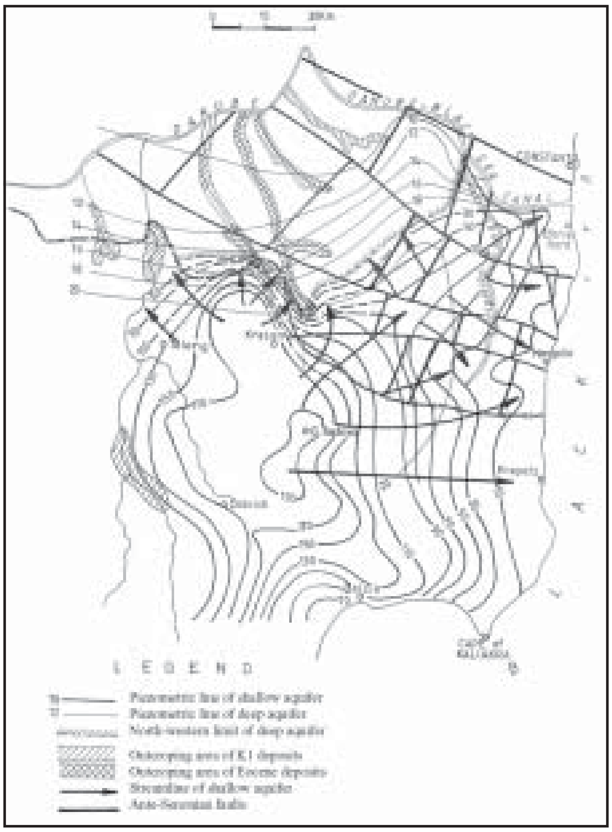

Figure 7. Regional hydrodynamic conditions for upper (shallow) aquifer. Conceptual model.

From hydrochemical point of view the water of the upper aquifer is mainly calcium-bicarbonate, with a total mineralization around 1 g/l. Locally, near the seaside, the content of Cl^- and Na^+ ions is higher (the water became of chloride-sodium type and the mineralisation can exceed 4 g/l). In the particular area of Mangalia Marsh, due to the relationship with the deep aquifer, the water became sulphurous.

Model Construction

In order to incorporate all the available geologic data a 3D numerical model is necessary. Moreover, because one of the key objectives of the study was to analyze the effects of the eventual agricultural pollution of the shallow aquifer on the well fields opened in the deep aquifer that includes the origin of water reaching a well, a fully three-dimensional representation becomes essential. The building of the model started from the boreholes information. Consequently, the elevation of each hydrostratigraphic unit was directly introduced from the boreholes data. To obtain spatially continuous elevations throughout the domain the spot values recorded in boreholes were interpolated using the universal krigging. The numerical model used in this study, FEFLOW, is a powerful finite element groundwater code that simulates also the mass and heat transfer. It uses both triangular and quadratic prismatic elements that allow to fit layers with variable thickness as well as the mesh refinement in zones with stronger gradient. One of the main advantages of the FEFLOW is the handling of the free surface in an unsaturated-saturated approach, which is essential when the free surface intercepts different hydrostratigraphic units. Vertically the aquifer system was divided into eight layers: two for the shallow aquifer and the aquitard and four for the deep aquifer. Being a transboundary aquifer and because of the lack of information from the Bulgarian part it was not possible to put on the model natural boundary conditions. In the southern part along the Romanian-Bulgarian border constant head boundary condition was imposed for the both aquifers as resulted from the piezometric surface. Along the Danube River and the Black Sea for the deep aquifer a transfer boundary condition was considered, while for the shallow aquifer the Black See level was imposed along the shore. The well fields were modeled by imposing their mean flow. Due to the three dimensional representation it was possible to take into account the imperfection in the well openings, while the filter were modeled by one-dimensional elements with large values of hydraulic conductivity.

Parameter identification

A simple visual examination shows the different flow pattern of the two aquifers. The shallow aquifer is an unconfined one the piezometry of which is a replica of the topographic surface, while in the same region the deep aquifer is a confined one. In the southern part there is a difference of 90 m in the piezometric heads in the two aquifers. The crucial point in the model calibration was to estimate the properties that are able to reproduce such a large head difference between the two aquifers. The common opinion was that the conductivity of the chalk aquitard was low enough to ensure this important head difference although until now no permeability test in the aquitard has been performed. On our knowledge the lowest reported value of the chalk conductivity was 10^{-8} m/sec (Freeze and Cherry, 1979). Even when an isotropic conductivity of 10^{-10} m/sec for the aquitard was used it resulted only a small difference of 30 m between the heads in the two aquifers. Several numerical tests demonstrate that only when consider a vertical anisotropy with lower values for the vertical conductivity for both aquifer and the aquitard this important head difference can be modeled. This hypothesis is supported by many visual examinations of outcrops that show the preferential horizontal orientation of the fracture in the both aquifers. The groundwater model was calibrated automatically for steady state conditions, using the model PEST as it is implemented in FEFLOW code. For the identification purposes the heads measured during the autumn of 1988, a year with the most intensive irrigation, were used as observation values. The code uses a nonlinear least-squares regression method where the optimal parameter values are estimated by minimizing the sum of squared residuals between the observed and simulated values of head. To avoid the overparametrization only the horizontal conductivity of the deep aquifer and the recharge were estimated, while the vertical conductivity of all layers and the horizontal conductivity of the shallow aquifer were kept constant during the iteration. The

Figure 8. Calibration of horizontal conductivity for deep aquifer.

uniform value of the horizontal conductivity of the shallow aquifer was suggested by the results of numerous pumping tests that indicate a small domain of variation, between 0.8-1.1 $\times 10^{-4}$ m/sec. Parameter identification was performed using a variant of the downscaling procedure (Laroque et al, 1999). The initial parameter mesh was made up by the polygons corresponding to the tectonic blocks. After the convergence each polygon was divided into four subdomains and the calibration was carried out again with the pervious values as guessed parameters. The procedure required only three refinements, the fourth leading to the same parameters field. It must be stressed that in this stage only the direct measured heads were used for the calibration without any supplementary interpolated heads as was suggested by Laroque et al.

The calibrated horizontal conductivity field of the deep aquifer covers a wide range of values (Figure 8), which corresponds to different degree of karstification. Generally, the calibrated conductivity agree with the results of the pumping tests indicating that even in the most karstified zones, at a large scale, the fractured rock can be equivalated with a continuous medium. The calibrated recharge field comprises values between 0.5-5.0 $\times 10^{-4}$ m/day with the largest values in the central and western parts of the shallow aquifer, which correspond in fact to the most intensive irrigated zones. In this region the leakage into the deep aquifer is increased due to the diminishing of the aquitard thickness or by a direct discharge when the aquitard pinches out.

For all the parameter zones the observed hydraulic heads present a strong trend along the unit-slope line (Figure 9), but the difference between the observed and simulated heads reduces as the refinement of the parameter mesh increases. Spatial distribution of the head residuals (Figure 10) shows that the poorest matches of the water levels occurred in the central part of the region, in a zone where the aquitard pinches up and the shallow aquifer discharges in the deep one. Numerous sensitivity tests carried out show that the parameter with the highest sensitivity is the vertical hydraulic conductivity of the whole aquifer system. As the Figure 11 shows the reducing with one order of magnitude of the shallow aquifer leads to a decreasing with 32 m in the hydraulic head of this layer. Similar results were obtained when reducing the vertical conductivity of the vertical conductivity of the aquitard or of the deep aquifer.

Model results

One of the aims of the study was to estimate the impact of the intensive agriculture developed

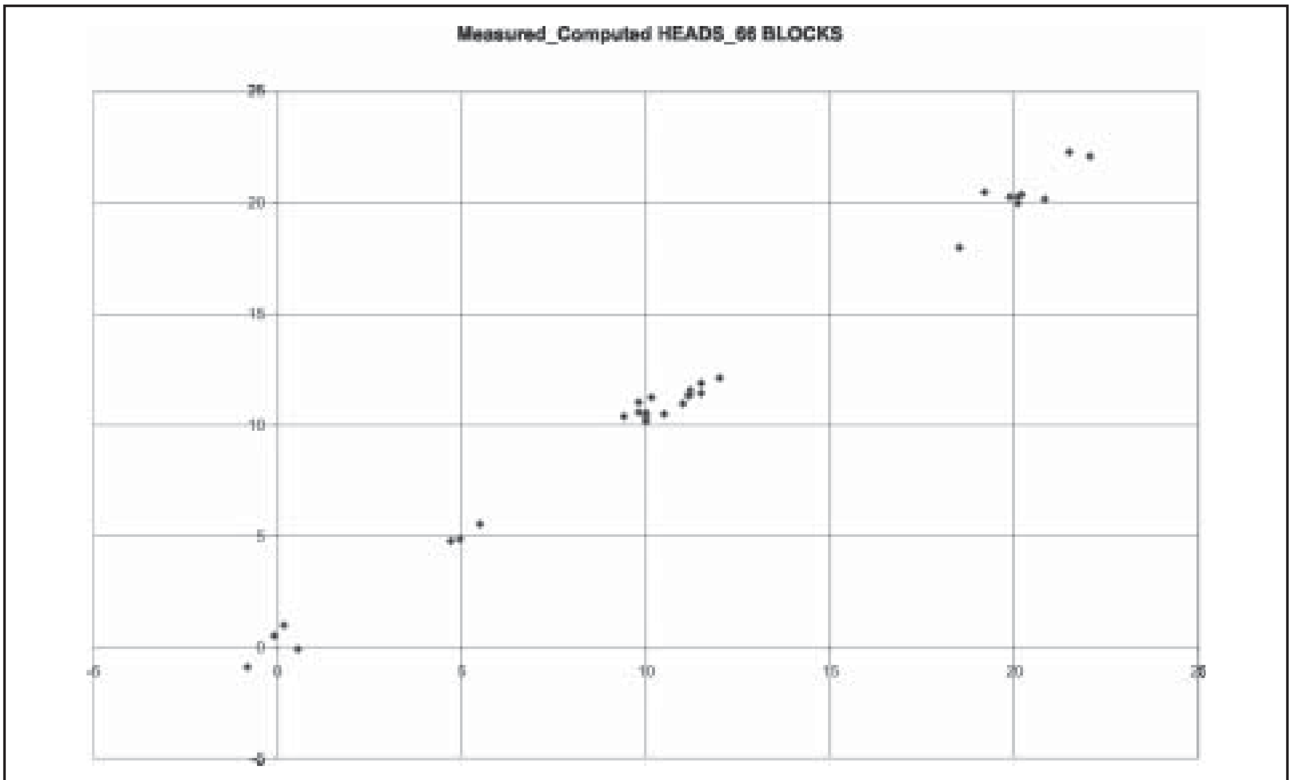

Figure 9. Measured vs Computed Heads.

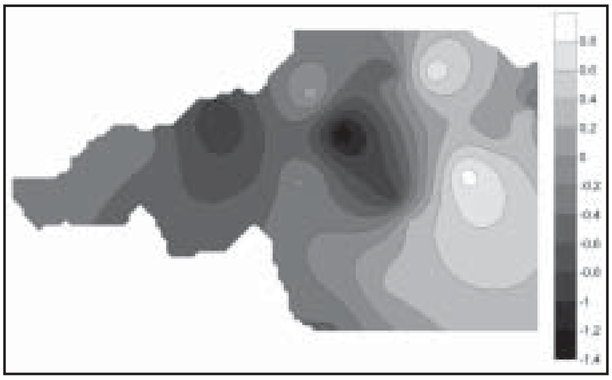

Figure 10

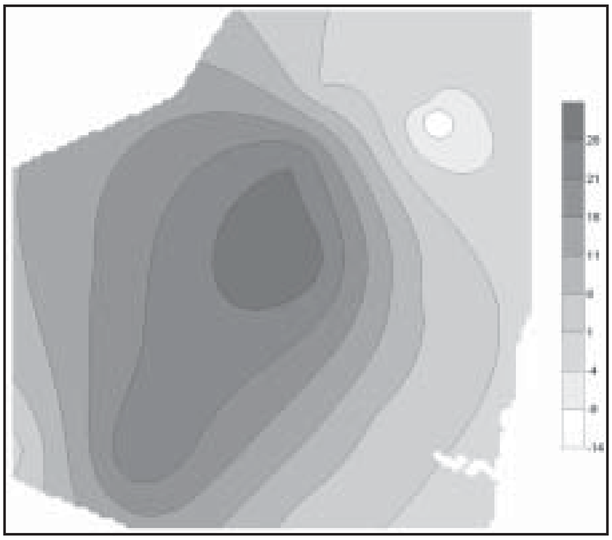

Figure 11

mainly in the shallow aquifer on the well fields opened in the deep aquifer. To achieve this goal both the flow capture of the well fields and the contaminant transfer were simulated. Figure 12 presents the capture zones of the most important three water tapings developed in the deep aquifer. One can observe that for all the wells the flow paths origins from the shallow aquifer in the region with the largest values of the recharge.

According to the flow capture it seems that due to the hydrogeological conditions the intensive agriculture carried out in the shallow aquifer could pollute the well fields opened in the deep aquifer. This conclusion was strengthened when simulate the steady state transfer of an ideal tracer, like the chloride, uniformly distributed over the zone with the largest recharge. The simulation was carried out by imposing a constant mass flux of 3 mg/m^3 day, which have led to a concentration of 320 mg/l, close to the value of 365 mg/l, measured in the zone. As the Figure 13 shows that the contaminant source initially distributed in a limited area spread out over a very large region and reaches the most important well fields in the both aquifers.

However the pollution risk appears to be much more reduced when the mass transfer was simulated in transient regime. Figure 14 presents the chloride plume 200 years after a continuous injection with the same mass flux of started. Although in this region the aquitard pinches up, due to the low values of the vertical conductivity the contaminant penetrates very slowly in the deep aquifer and spreads out only over a limited area.

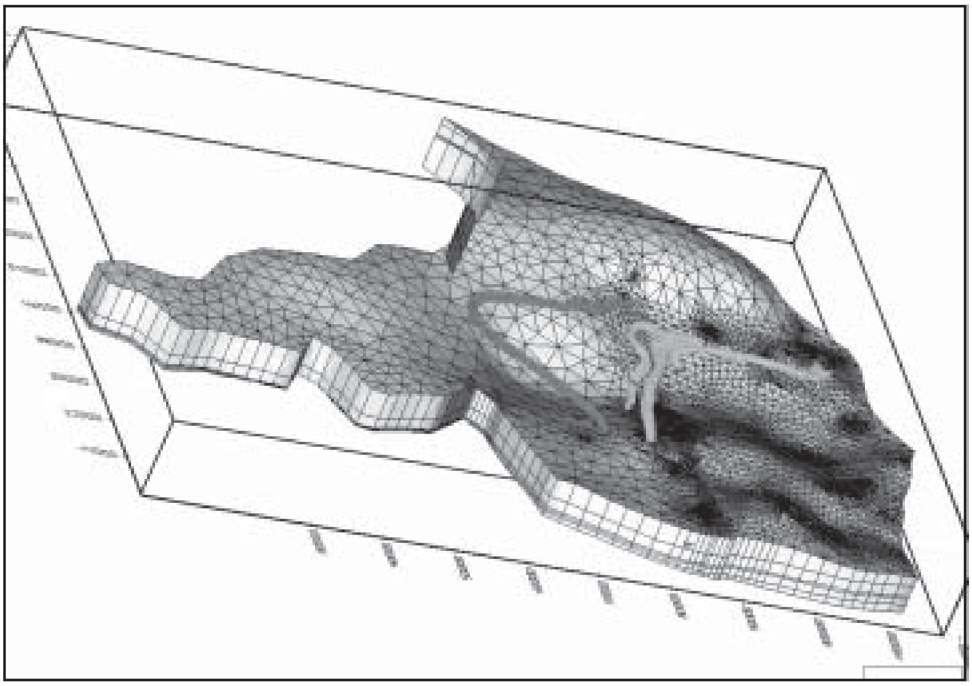

Figure 12. Capture zones.

Figure 13. Spreading of contaminant.

Figure 14. Plume of chloride 200 years after injection.

Conclusions

At the scale of whole Southern Dobrogea area there are complex relationships between surface water (littoral lakes, Danube-Black Sea Channel, irrigation system) and the groundwater of the two aquifers, also in connection. For example, the quality of water from Danube-Black Sea channel affects directly (and quickly) the groundwater tapping; the channel water, used for irrigation, combined with pesticides and fertilizers effects, determine the water quality of the upper (sarmatian) aquifer and further, in time, the deep aquifer one (starting from the zones with unconfined regime).

These two aquifers from Southern Dobrogea belong to a regional, transboundary carstic aquifer system. The long term exploitation and sustainable management require studies at the scale of its natural boundaries.

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References

Freeze R.A., Cherry J.A. (1979) Groundwater: Englewood Cliffs. NY, Prentice Hall.

Laroque M., Banton O., Ackerer P., Razack M. (1999) – Determining karst transmissivities with inverse modeling and an equivalent porous media. Groundwater, 37 (6).

Machkova M., Lichev A., Pulido Bosch A., Velikov B., Dimitrov D., López-Chicano M. (1998) – Some stable isotopes in the ground waters of the Malm-Valanginian and Sarmatian aquifers in the Dobroudja Region (NE Bulgaria). Comptes Rendus de l'Académie Bulgare des Sciences, 51 (11-12): 73-76.

Pulido Bosch A, Machkova M, Calvache ML, Calaforra JM, Dimitrov D, López-Chicano M, Velikov B, Pentchev P (1996) – Hydrogeological of the Upper Aquifer, Dobrich region Northeastern Bulgaria. Hydrogeology Journal, 5 (2): 75-85.

Zamfirescu Fl., Moldoveanu V., Pitu N, Danchiv Al., Nash Harriet (1994) – Vulnerability to pollution of karstic aquifer system in Southern Dobrudgea. Proceedings of RAH International Symposium "Impact of Industrial Activities on Groundwater", Constanta, Romania.

Zamfirescu Fl., Danchiv Al., Popa I., Popa Roxana, Rudolph-Lund K. (2005) – The carstic aquifer system of Southern Dobrogea (Romania). Proceedings of IAH Conference on «Water Resources and Environmental Problems in Karst», Belgrad – Kotor, Serbia & Montenegro.