MINISTRY OF EDUCATION AND RESEARCH

TECHNICAL UNIVERSITY OF CIVIL ENGINEERING BUCHAREST
FACULTY OF HYDROTECHNICS

- PhD THESIS -

- SUMMARY -

RESEARCH ON THE INFLUENCE OF DEVELOPED WATERWAYS UPON WATER SOURCES FROM FISSURE-KARST AQUIFERS

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1. INTRODUCTION

This scientific thesis aims to present the results of research on the influence of developed waterways on water sources in fissure-karst aquifers.

The choice of the topic was also determined by the existence of such a case in Romania, located in Southern Dobrogea, where the Danube - Black Sea, respectively Poarta Albă – Midia, Năvodari waterways are exploited during the construction of which the most important fissural - karst aquifer in the country was intercepted, whose groundwater is extracted in large quantities for the water supply of the population of the region.

The existence of the developed waterways has caused local changes in the flow regime and quality of groundwater in the karst-fissural aquifer systems, both during the construction period and after the operation.

In his PhD thesis, the author aimed to assess the influence of waterways on the flow regime and groundwater quality in the fissural karst aquifer system and on the safe functioning of local water supply systems after approximately 35 years of operation.

At the same time, the possibility of identifying methods for systematic verification of the functioning of groundwater catchments located in the vicinity of waterways was examined, with the aim of preventing and reducing risks in operation.

The main research ideas of the thesis are:

- The current state of national and international knowledge of the influence/interference of developed waterways on aquifer resources and, in particular, on water supplies.
- Study the identified interdependence factors between waterways and physico-carst aquifers.
- Experimental research on a case study in Constanta county, with the following components of analysis: evaluation, processing and interpretation of existing data for the identification of geometrical, hydrophysical and hydrochemical characteristics of the analysed environments; correlations of the identified characteristics with the operation of the waterways and the groundwater flow regime; criteria for the design and implementation of a monitoring system of quantitative and qualitative parameters of groundwater; carrying out monitoring, data processing, interpretation of results, possible correlations.
- Analysis of waterway design solutions from the point of view of hydraulic relations with the aquifer: evaluation of influencing parameters on the qualitative and quantitative groundwater balance.
- Analysis of groundwater catchment design solutions (location and characteristics) exploiting physicochemical aquifers hydraulically related to the developed waterways.

The results obtained in the experimentally researched area can contribute to the development of knowledge of this very important sector, which is part of a region of strategic importance both for the existence and protection of the most important fissural-karst aquifer system in Romania, as well as for maintaining safety in exploitation of the water supply systems of the coastal sector in Constanța county.

2. GROUNDWATER CIRCULATION AND POLLUTION MECHANISMS

2.1 General characteristics

Karst groundwater resources are found confined in various types of rock, through which, as a result of physical or chemical processes, they create different circulation/transit pathways. The aquifer layers that store the water volumes can be uneven and inhomogeneous, which leads to difficulties in the mathematical expression of flow laws.

Franciss analyses representative elemental volumes for quasi-homogeneous rock masses, both physically and statistically, but will always be associated with a chosen class of lithological or structural features. Physically, the minimum size of an analysed volume from which significant average results will be obtained, which can then be generalised to the whole volume of a fractured quasi-homogeneous rock mass.

The actual movement of groundwater through a discontinuous porous or fissural medium is simplified into an apparent movement through a continuous medium (solid+golids), with the condition that the flow rate through the section is identical to the actual flow rate. [61] Thus, the notion of filtration velocity (apparent velocity) is introduced, defined by the relation:

$$V = \frac{Q}{A} \qquad (1.1)$$

where: Q – the flow passing through a section
A – the total area of the section

The discontinuous medium is equivalent to a continuous one using averaging over the representative elementary volume of the characteristics and being dependent on: [61]

- the point position;
- the chosen feature;
- extension of the spatial domain where mediation is performed.

2.2 Flow parameters and general equations

The main flow parameters such as porosity, permeability, piezometric load and hydraulic gradient are presented in detail, as well as the laws of flow in porous and karstic-physiological media and the continuity and hydraulic diffusivity equations.

2.3 Issues of pollution mechanisms

The transport phenomena of miscible pollutants are presented: molecular diffusion, advection, mechanical and hydrodynamic dispersion, respectively transformation, retardation and attenuation processes of dissolved substances.

3. WATERWAYS AND INTERACTION WITH GROUNDWATER

3.1. Construction concepts of waterways

The term "waterway" refers to all the transport ways that can take place on a river, lake or canal that does not belong to a sea and which by natural or man-made means allows navigation.

Depending on the type of craft to be navigated, waterways shall be so constructed as to provide a width and depth of water optimum for safe navigation. Depending on the elevation of the natural terrain, fairways may be excavated or filled in. Water losses through seepage can be significantly reduced by requiring sealing and lining of channels. [54]

Increasing the efficiency of ship operations can be achieved by applying constructive methods to natural water courses. One of these methods is channelisation of water courses and involves damming the bed in favourably chosen areas to transform the natural flow under a continuous slope into a stepwise flow. Boats move through these steps by means of sluices or lifts.

3.1.1. Waterways routings

The optimal route of a waterway is characterised by a minimum, predominantly linear length, without many sinuosities, chosen in such a way as to have a limited volume of earthworks and to generate the lowest possible investment costs.

In order to ensure the safe and optimal operation of waterways, the following assumptions should be taken into account when choosing the route: [54]

- The behaviour of the soil under the action of water;
- The possibility of landslides of slopes.

The choice of route for wide waterways is determined after a preliminary geological survey, which includes the digging of wells of varying depths depending on the hydrogeological conditions at the site.

3.1.2. Longitudinal profile

The configuration of the longitudinal profile of a waterway is determined according to the relief of the natural terrain and the groundwater level, so as to allow as much as possible a gravitational flow of water.

In the case of wide waterways, the routes shall be structured in step bays, and sizing shall be according to the following specifications: [21]

- The length of the bays is recommended to be as long as possible;
- The number of retention steps is recommended to be as small as possible and with equal heights;
- The configuration of the reaches should ensure optimum navigation speeds.

3.1.3. The cross-section

The cross-section of waterways can have different shapes: rectangular, trapezoidal, double-sloped, bed-shaped, semicircular or parabolic, shown graphically in Figure 3.1.

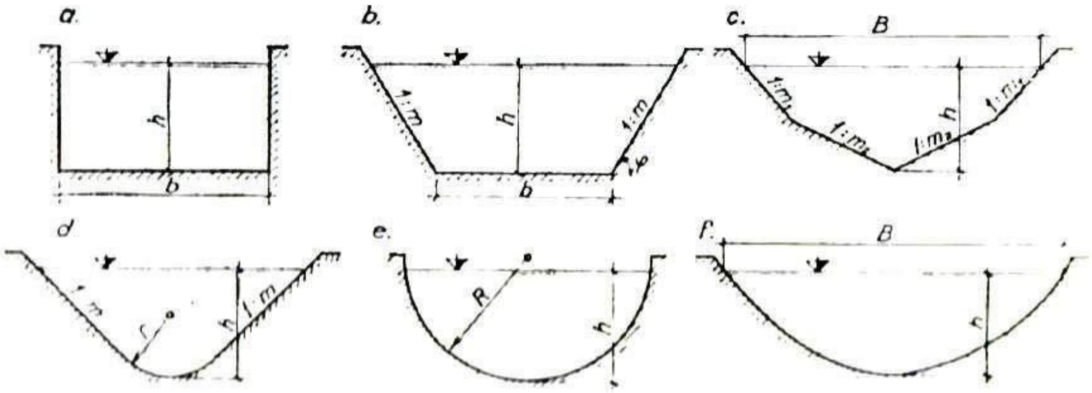


Figure 3.1. - *Types of waterway cross sections*
a - rectangular, b - trapezoidal, c - double slope, d - bed-shaped,
e - semicircular, f - parabolic [54]

In practice, cross-sections with rectangular, trapezoidal or parabolic geometric shapes are usually used because they are hydraulically optimal and easy to execute. "In Figure 3.1, the first three types of cross-sections (a, b, c) are used for channels in earthen terrain, while the following (d, e, f) are used in rocky terrain." [54] The parabolic cross-section shape is used for deep waterways, which require the slopes of the land to be as gentle as possible and converge towards the bottom of the channel to ensure the stability of the banks.

3.1.4. Slope protection

Typically, fairway slopes are prone to degradation over time mainly due to climatic action (temperature and winds) and wave action produced by boats during navigation. In order to ensure optimal and safe operation of waterways, constructive measures to protect slopes from degradation and slope instabilities should be adopted.

As a rule, slope protection works are carried out with concrete and stone linings, as both materials retain their characteristics regardless of climatic and working conditions.

3.1.5. Waterproofing of waterways

From a structural point of view, waterways should be waterproofed to eliminate the risks of water loss through seepage and accidental groundwater pollution in the event of contamination in waterways.

Over the years, a number of works have been used to waterproof waterways, such as: bituminisation, injection of silicates or other chemical thinners, treatment with cement or resins, laying of impermeable layers, use of coatings, sealing screens or sealing of the channel bed.

To avoid water loss through seepage from the sewer, sealing screens can be made of clay, concrete, etc., extended until an impermeable layer is reached. [40]

3.2. Waterways in the world

The main waterways in the world are presented: The Grand Canal of China, Canal du Midi, Suez waterway, the Main-Danube waterway and Panama waterway

3.3 Construction characteristics of the investigated waterways

3.3.1 Construction characteristics of the Danube-Black Sea waterway

The Danube-Black Sea waterway was built between Cernavodă (km 299.3 on the river) and the Black Sea (Constanta South port), totalling a length of 64.41 km.

From a construction point of view, two twin locks were provided on the route of the waterway, at Cernavodă and Agigea. [7] The role of these hydrotechnical constructions is to ensure the connection of the waterways with the variable levels of the river, i.e. to allow

The waterways was structured in three sections, as follows: [7]

- **Section I**: located between the Danube and the upstream head of the Cernavodă lock, 4.105 km long;
- **Section II**: located between the downstream head of the Cernavodă lock and the upstream head of the Agigea lock, totalling 57.991 km in length;
- **Section III** located between the downstream head of the Agigea lock and point "0" in the fluvio-maritime aquarium of the port of Constanța Sud, with a length of 1,510 km.

3.3.2 Construction characteristics of the Poarta Albă - Midia, Năvodari waterway

The Poarta Albă - Midia, Năvodari waterway was built between Poarta Albă, at the junction of the Danube and the port of Midia and totals a length of 27.50 km. The eastern branch of the waterway extends 5.0 km through Lake Tașaul (Năvodari). [8]

The route of the waterway crosses Valea Adâncă (Nazarcea), passes through the Ovidiu plateau, through the limestone quarry area, bypasses the northern vicinity of Lake Siutghiol (Mamaia) and flows into the port of Midia. A branch of the waterway reaches Lake Tașaul, as far as the port of Luminița. [8]

From a construction point of view, two locks were provided on the route of the waterway, at Ovidiu and at Midia - Năvodari. The role of the lock at Ovidiu is to ensure the passage from the water level in gauge I + 7.50 mrMB to the level of 1.25 mrMB in gauge II, which represents the average level of exploitation of lakes Siutghiol and Tașaul. The Midia - Năvodari sluice has been provided in the area where the waterway flows into the sea, to ensure the transition from the level of the waterway to the level of the Black Sea. [8]

The role of these hydrotechnical constructions is to ensure the connection of the waterway with the variable levels of the river, i.e. to allow communication with the level of the Black Sea.

The waterway was structured as follows: [8]

- **Section I**: located between the outlet of the second section of the Danube-Black Sea waterway and the upstream head of the Ovidiu lock, with a length of 15.230 km;
- **Section II**: located between the downstream head of the Ovidiu lock and the upstream head of the Midia - Năvodari lock, with a length of 10.041 km;
- **Section III**: located between the downstream head of the Midia - Năvodari lock and the Midia seaport, with a length of 1.834 km.

4. ENVIRONMENTAL, GEOLOGICAL AND HYDROGEOLOGICAL CHARACTERISTICS OF THE STUDIED AREA

4.1. Geological and structural tectonic conditions

In order to carry out the studies and research in the area of exploitation of the waterways, the geological and structural tectonic conditions at the level of current knowledge were reconsidered.

The research area is bounded to the north by the Capidava - Ovidiu structural fault, to the south by the Rasova - Costinești fault, to the west by the Danube River and to the east by the Black Sea. The whole area studied is part of Southern Dobrogea and structurally it represents a sector of the Moesic Platform.

This area presents typical platform characteristics, and the predominant presence of brittle limestone rocks allowed the fracturing of the entire sedimentary cover into tectonic blocks delimited by vertical or subvertical faults.

The reaction of the area to the mechanical actions of rock deformation was to move the resulting blocks both vertically and horizontally.

The structural map of the investigated area (Figure 4.2.) was made on the basis of the information obtained during the drilling on site and geophysical measurements specific to the study of geological structures. Geological sections (Figure 4.3.) were also made on this occasion, which provide an understanding of the geological conditions of the waterway site. From a structural tectonic point of view, the following can be observed:

- Two fracture systems (faults) on the NNE - SSV and VNV - ESE directions, which generated the separation of tectonic blocks of different sizes.
- The NNE - SSV faults are older faults that have undergone predominantly vertical movement.
- The VNV - ESE oriented faults are newer faults and have both vertical and horizontal movements, which have resulted in fragmentation and spatial offset of the NNE - SSV faults.

Through the structural map and geological sections of the investigated area, 13 major structural blocks were highlighted, which are characterized by different thicknesses and permeabilities. Basically, these carbonate deposits constitute the rock that stores significant groundwater resources (see structural map and geological sections). The configuration of the geological structure, which highlights the existence of fault-formed blocks, makes it possible to correctly interpret the hydrodynamic conditions of the investigated area and the local interactions between the waters of waterways and the existing fissure-karstic hydrostructures.

GENERAL LAYOUT

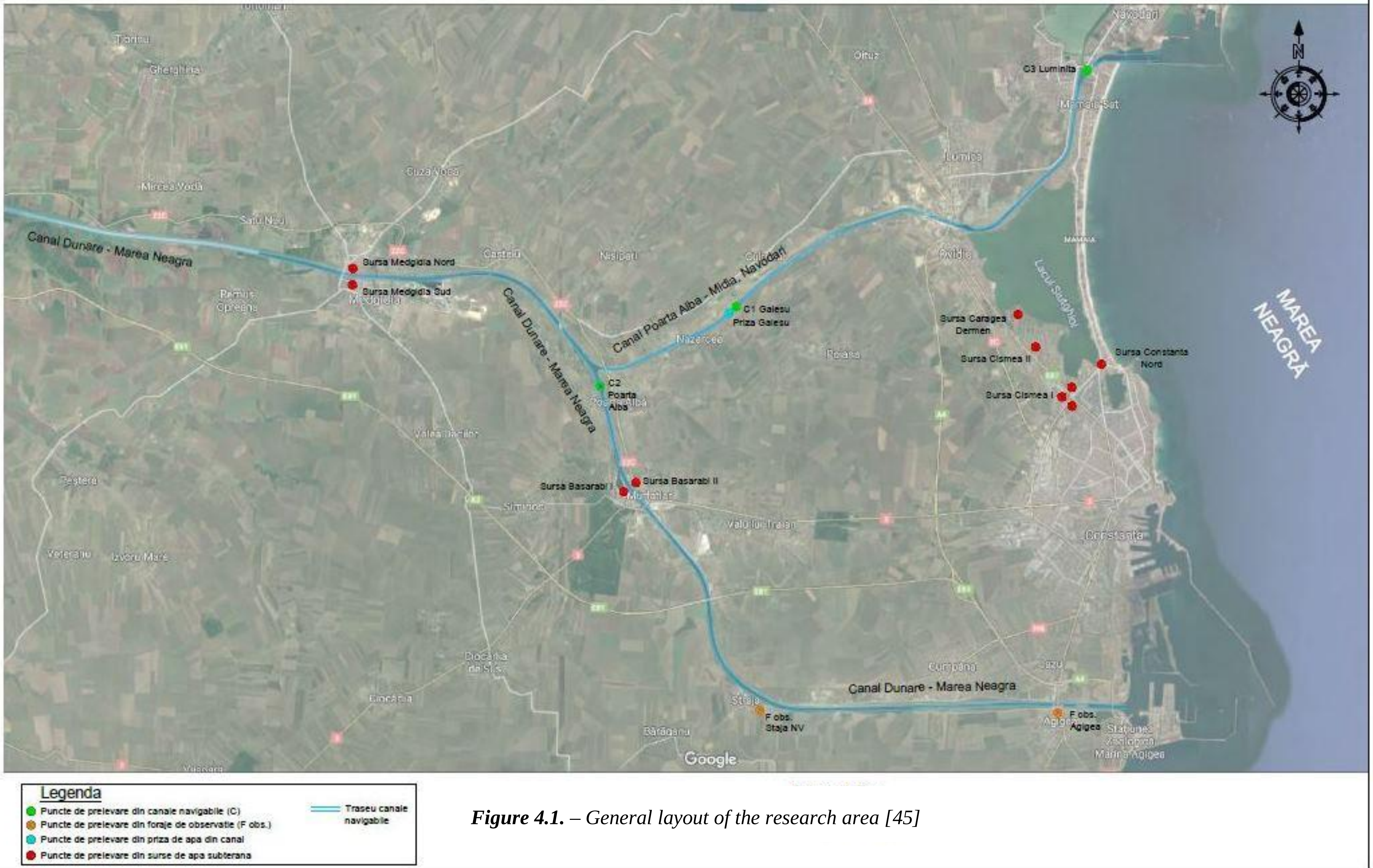
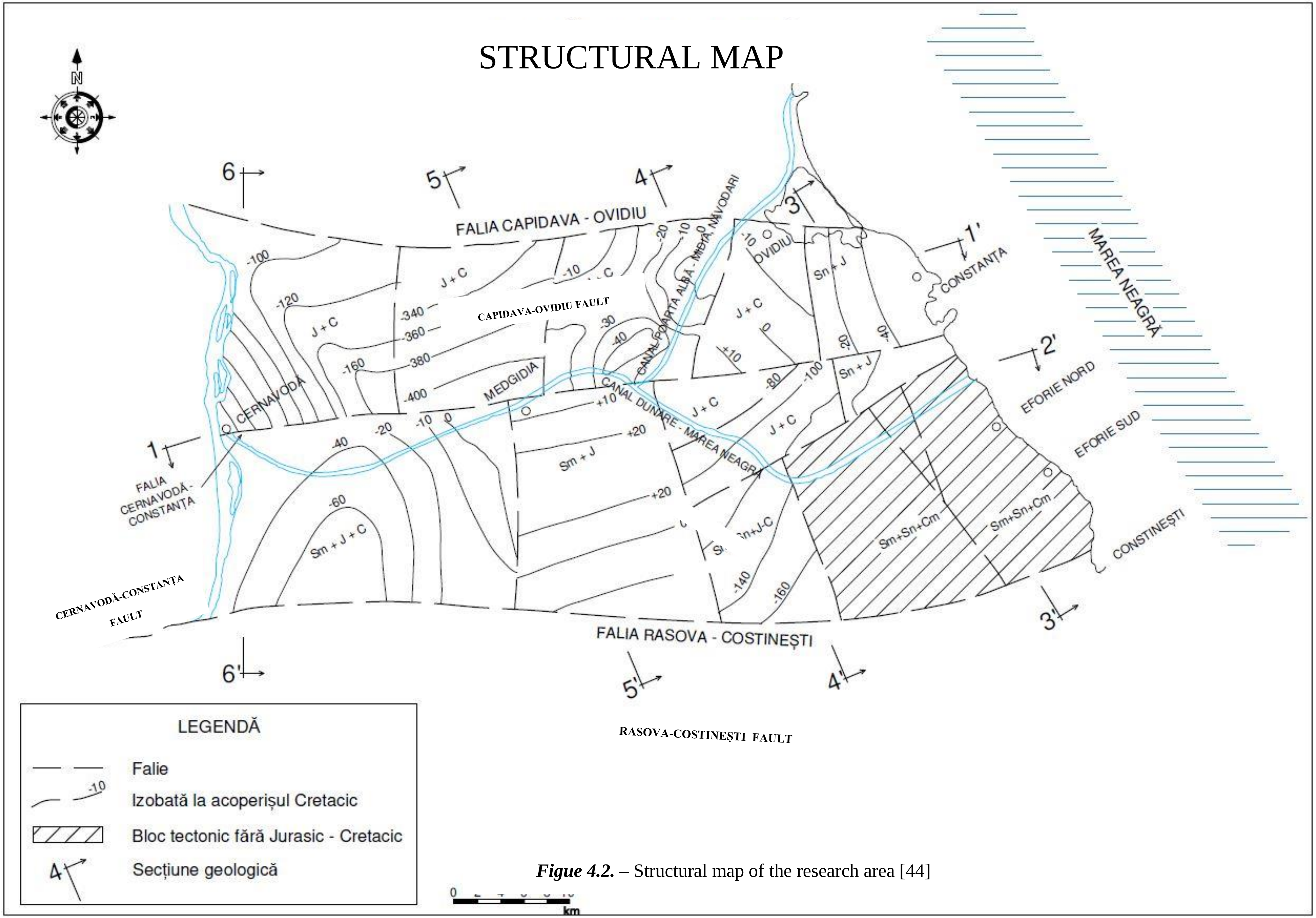


Figure 4.1. *– General layout of the research area [45]*



Figue 4.2. – Structural map of the research area [44]

GEOLOGICAL SECTIONS

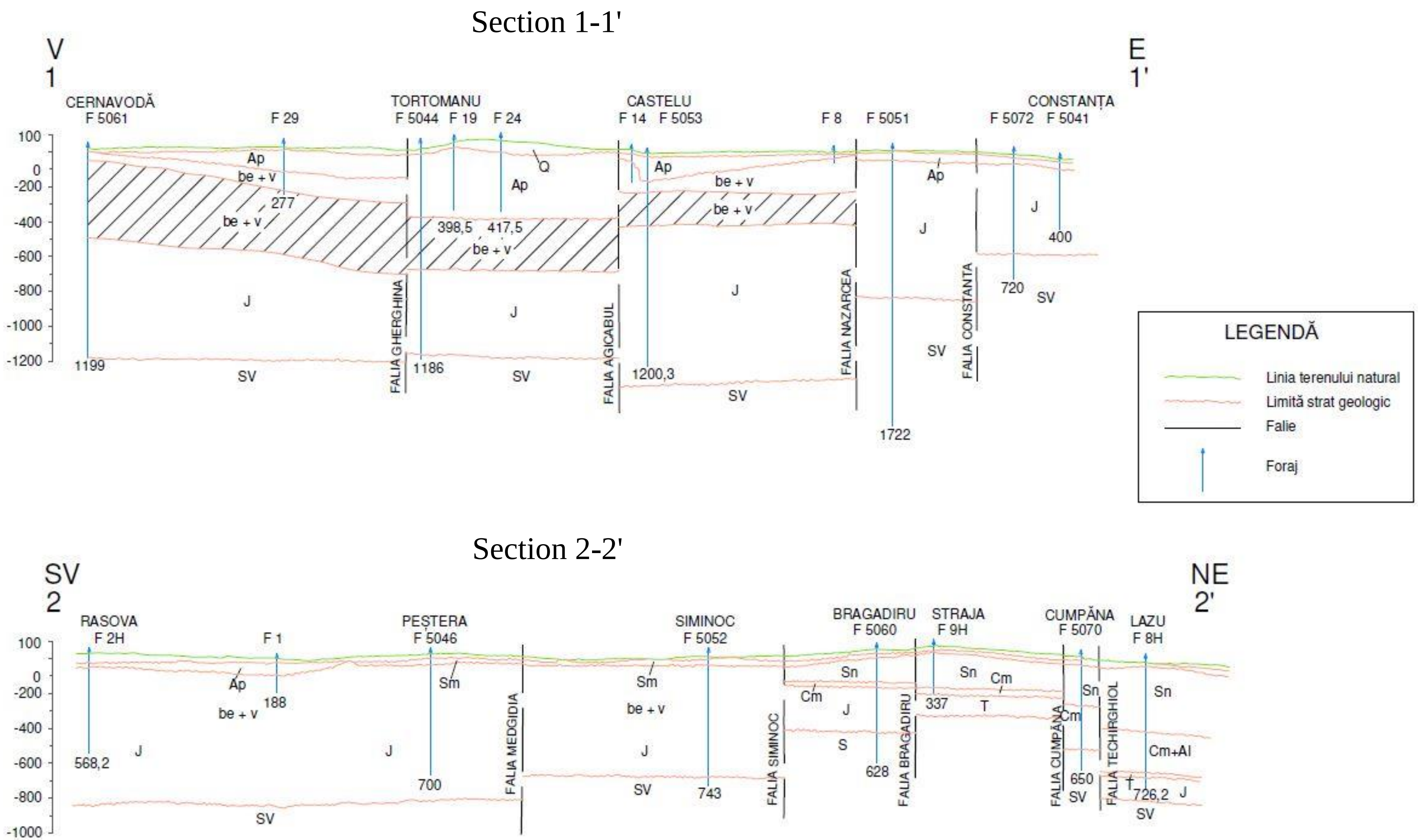


Figure 4.3. – Geological sections 1-1' and 2-2' of the research area [44]

4.2. Geomorphological conditions

Most of the territory of Dobrogea, where the Danube - Black Sea and Poarta Albă - Midia, Năvodari waterways are located, has the appearance of a plateau whose altitude decreases from north to south, up to the Carasu Valley, and then increases towards the south.

The depressed area along the Carasu Valley, on which the Danube - Black Sea waterway is located, is also called the Carasu Culvert.

4.3. Hydrological conditions

From the point of view of the hydrographic network, the surveyed area is generally poorly developed. The valleys are mostly waterless or temporarily fed by rainfall and irrigation systems.

In this area the water network is formed by the following watercourses: Danube (137 km long) and the Carasu Valley, whose catchment area stretches as far as Palas (the tributaries of the valley are dry for most of the year).

A number of natural lakes and lagoons can be found in this area: Siutghiol, Tașaul, Corbu, Tăbăcarie, etc.

Lake Siutghiol is fed from the lower aquifer (Jurassic limestones) by springs located on the bottom of the lake. The basin of the lake was formed as a result of karst phenomena in the post - Jurassic period. The lake is fed by groundwater springs along the Capidava - Ovidiu fault, which crosses the lake.

The Danube - Black Sea and Poarta Albă - Midia, Năvodari waterways are of particular importance for the water regime of the area. Built 40 years ago along the former Carasu valley, they link the Danube to the Black Sea from Cernavodă to Agigea and Năvodari.

4.4. Climatic conditions

80% of the climate of the area is temperate-continental, specific to the plains, and about 20% is influenced by the maritime climate, specific to coastal areas.

The average annual temperature fluctuates around 11 °C. The absolute maximum temperature in the area surveyed was recorded at Cernavodă on 20 August 1945, at 42,2 °C, and the absolute minimum temperature at Murfatlar on 25 January 1941, at -33,2 °C.

The average annual precipitation is unevenly distributed in the area surveyed, totalling less than 500 mm, i.e. 478 mm at Cernavodă and 467 mm at Constanța. Most of the precipitation falls in the warm season in the form of showers. In summer, cloudiness is reduced and the sunshine duration exceeds 10 to 12 hours per day. [34]

4.5. Hydrogeological conditions

The location of the Danube - Black Sea and Poarta Albă - Midia waterways, Năvodari is hydrogeologically characterized by a diversity of strata and aquifer complexes that are in continuous interaction with surface waters and the Black Sea.

The main criteria on which the inventory and study of the main hydrostructures were based are:

- degree of horizontal and vertical extension;;
- economic importance;
- degree of knowledge of the hydrodynamic regime;
- groundwater quality;
- degree of knowledge of vulnerability to pollution.

The hydrogeological studies carried out have highlighted the hydrogeological complexity existing in the area, but simplifying it, we find the existence of a number of five aquifers confined in rocks: Quaternary, Sarmatian, Eocene, Senonian and Upper Jurassic - Lower Cretaceous aquifer complex.

4.5.1 Upper Jurassic - Lower Cretaceous (lower) aquifer complex

In terms of hydrodynamic resources, it is the most important aquifer complex in the area, both in terms of regional development and thickness (the calcareous karst deposits can reach up to 1200 m), and in terms of the physical-chemical and bacteriological quality of the water flowing through it.

In the investigated area, this aquifer complex operates under pressure, with the exception of a small sector in the vicinity of the Danube River. It is therefore an aquifer largely protected in terms of vulnerability to pollution.

Groundwater circulates under pressure conditions (through channels, faults, large fissures, porous media, microcapillary cracks) by rising and falling through voids by chemical dissolution processes.

The degree of cracking was found to be spatially non-uniform. For the vertical component, it was found based on experimental pumping that cracking is generally higher at the top of carbonate formations. "Actual transmissivity values of the Upper Jurassic-Lower Cretaceous aquifer complex range from a few tens or hundreds of m^2/day to more than 150,000 m^2/day". [50]

The northern boundary of this aquifer complex is the Capidava - Ovidiu structural fault, which separates southern Dobrogea from central Dobrogea and is a sealed boundary.

The discharge zones of this hydrostructure are represented both by Lake Siutghiol (in small proportions), located in the coastal area of Constanta, and by the Black Sea (in large proportions).

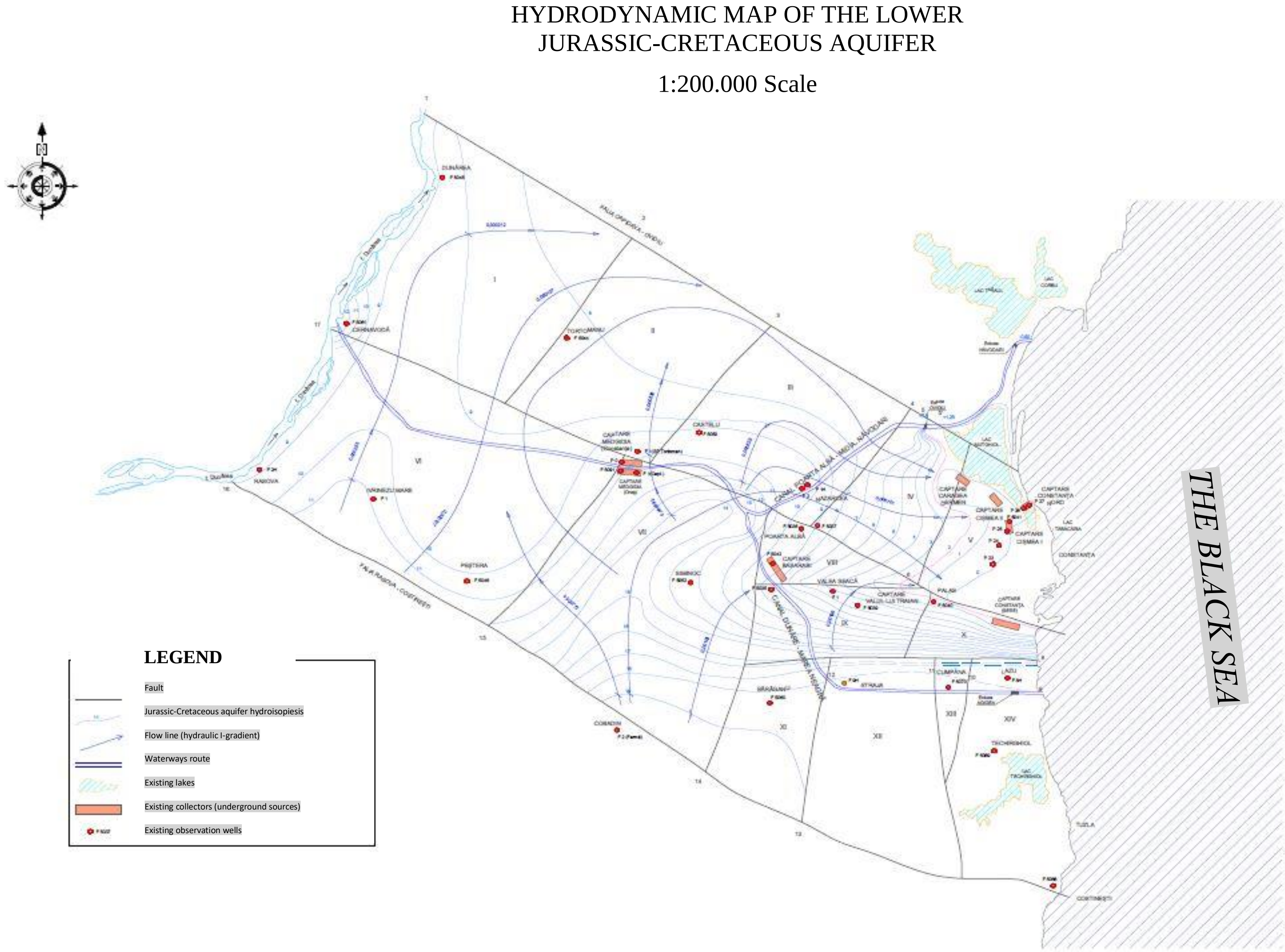


Figure 4.4. – Hydrodynamic map of the research area [44]

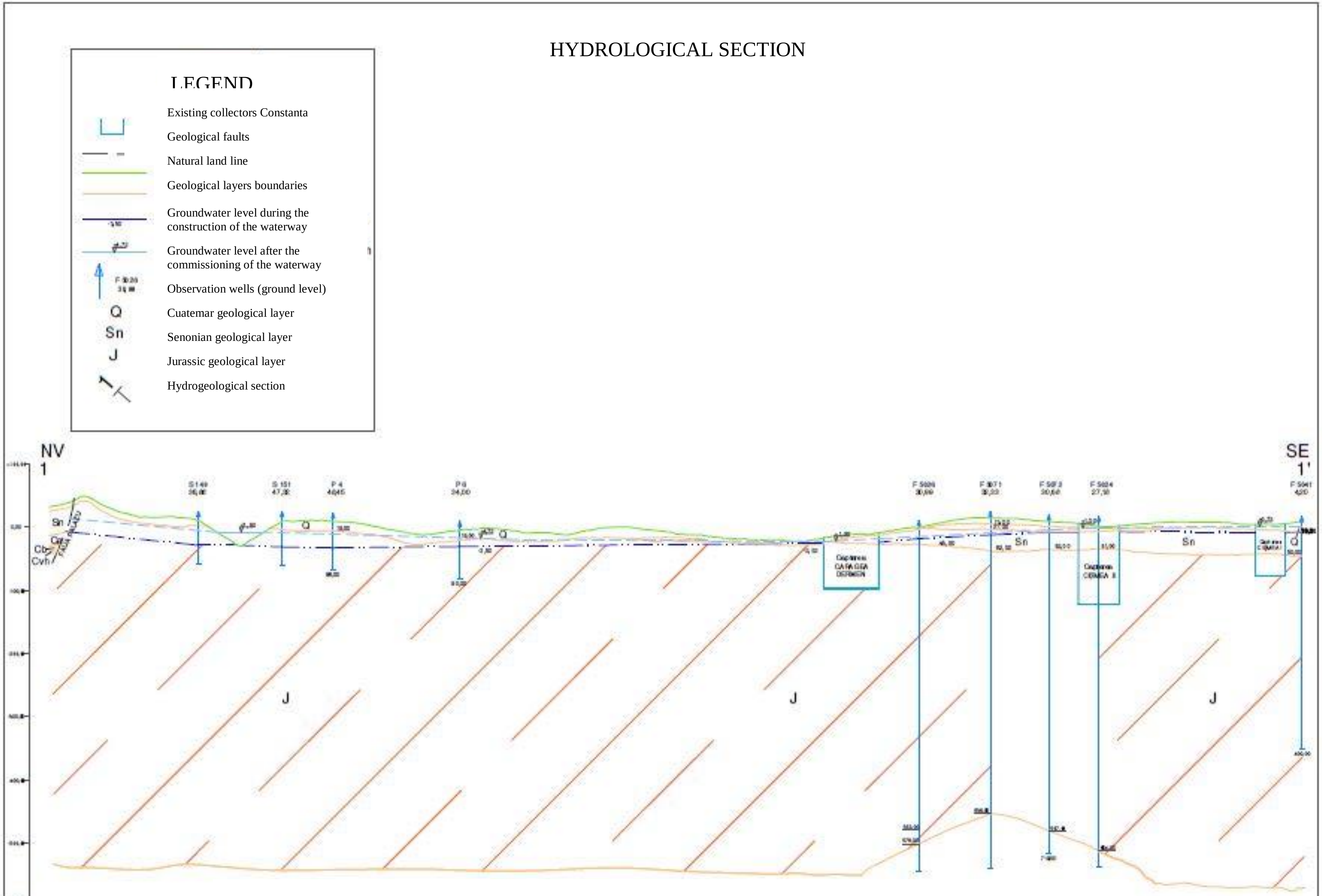


Figure 4.6. – Hydrodynamic map of the Jurassic - Cretaceous (lower) aquifer in the investigated area [44]

5. SURVEYS OF WATERWAY SITES

5.1. Hydrodynamic elements of karstic fissural aquifers

5.1.1. Hydrodynamic elements specific to karst aquifers

Fissure-karst aquifers are confined in carbonate rocks (limestones, dolomites) and have a lattice-like structure formed by dissolution processes. The structure of karstic aquifers includes fissures (capillary or over-capillary), voids (conduits or channels) and even caves through which groundwater flows.

The karstification of carbonate rocks occurs from the earth's surface through shallow flow and proceeds through dissolution processes in fissure and fault zones.

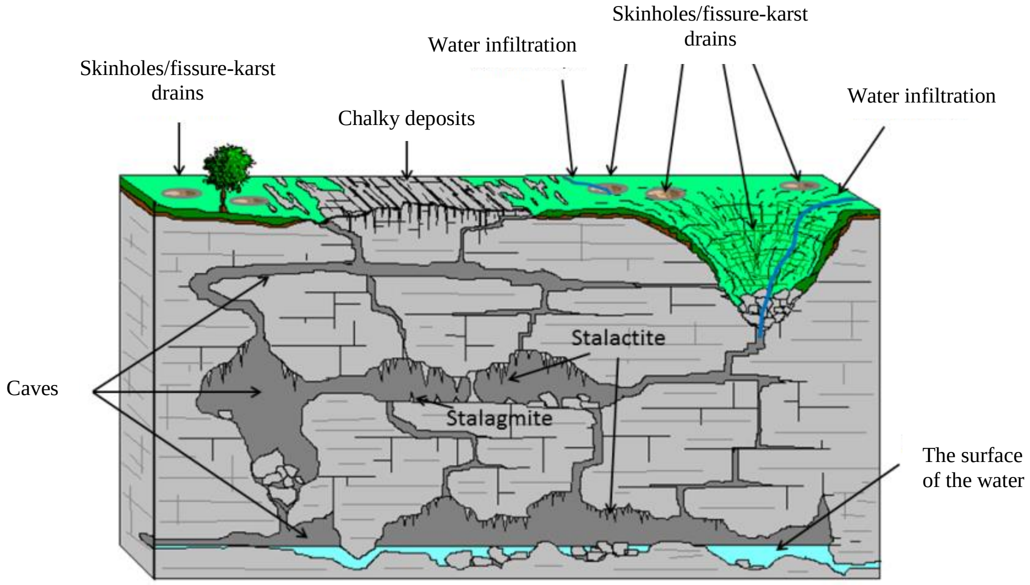


Figure 5.1.

Figure 5.1. – Landforms found in karst [95].

Empirical methods have led to the conclusion that drainage systems in karst-fissure aquifers extend from recharge to discharge zones. In other words, water infiltration and dissolution processes contribute to the widening of the entire crack system located in the adjacent aquifer recharge zones. The widening of the fissure system will decrease proportionally to the advance of water towards the discharge zones, and eventually in the discharge zone the entire flow will be accumulated in a small number of channels or in some cases in one channel, as shown in Figure 5.2 [59].

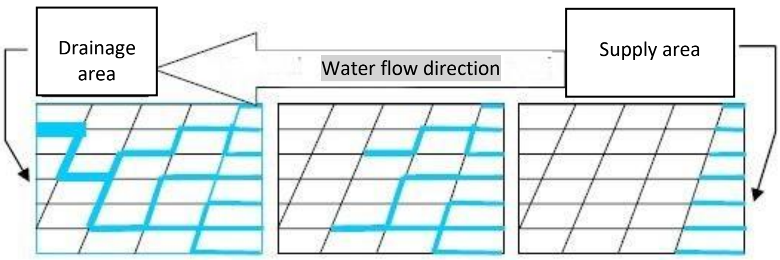


Figure 5.2. – Drainage system development in fissural aquifers - karst [29] [59]

Water flow through cracks is usually at low velocities, flowing in a laminar regime, but as karstic voids enlarge, water flow will be at higher velocities and flow will be turbulent.

In terms of vulnerability to pollution, karst aquifers are prone to pollution during major recharge events, when a large amount of groundwater infiltrates and the flow regime in the aquifers can change radically. [31]

5.1.2. Quantitative interaction between waterways and aquifer

The study of the quantitative interaction between waterways and aquifers can be done by adopting hypotheses depending on the natural flow regime in the investigated area. In this area, on a regional scale, no significant changes in hydrological and hydrogeological data have been observed since the commissioning of the waterways (last 30 years). Under these conditions, for the study of quantitative interaction, the assumption of a steady-state - conservative flow regime is adopted and the modified mathematical expressions of the general hydraulic diffusivity equation and its adaptation to the established assumptions are presented. Assuming that the medium of motion is isotropic (transmissivity is constant regardless of the direction of motion) the mathematical expression reduces to the Laplace equation.

Particularizations of the general hydraulic diffusivity equation for vertical plane currents with uniform, non-uniform and mixed hydraulic motion (applicable in the studied area) are also presented.

Also in this area, but at the level of local studies of the quantitative interaction between channels and the aquifer complex, it is possible to adopt the hypothesis of steady-state - non-conservative flow (Murfatlar area) and the particularised hydraulic diffusivity equation results.

5.1.3. Hydrogeological investigations in the waterway area

In the study area, the majority of the population's water needs are provided by the groundwater resources of the Jurassic-Cretaceous (lower) aquifer complex.

The Jurassic-Lower Cretaceous aquifer complex extends over the whole territory of Southern Dobrogea, which gives it a unitary character. The aquifer complex is mostly under pressure on the scale of the Southern Dobrogea territory (about 60% of the territory) and with free level in the vicinity of the Danube river and in the southern part. In the areas where it is with free level, the aquifer complex can be loaded directly by seepage from the precipitations, irrigation canals and by vertical drainage from the upper (Sarmatian) aquifer.

The hydrogeological investigations carried out in the sector where the Danube - Black Sea and Poarta Albă - Midia, Năvodari waterways are located, required the use of existing hydrogeological wells, both for in situ measurements and for the use of data for the calculation of transmissivities.

The research carried out was based on the following steps:

- selection of study or even production wells to form a monitoring network for the aquifer system in the area;
- inventory and reinterpretation of data from previous hydrodynamic tests (from the execution of the wells), where imperfections according to the degree of openness of

the aquifers and the hydraulic resistances of the vertical flow (being wells with large depths) were taken into account;

- calculation of some hydrogeological parameters (especially transmissivity, necessary for knowledge of groundwater resources);
- study of the variation of specific flow rates as a function of depth.
- hydrogeological mapping in the area where the waterways are located.

Depending on the types of data available, the selection of wells for the investigation of the Jurassic - Cretaceous aquifer was made taking into account several criteria: location of the wells, lithology of the ground at the time of drilling, type of aquifers intersected and hydrodynamic tests during drilling.

Crt. No.	**Place**	**Obs. Well**	**Land level [m]**	**NHs (2018)**
				Levels [m]
1	Basarabi (Murfatlar)	F 5035	15.88	7.10
2	Poarta Alba	F 5036	23.07	13.15
3	Poarta Alba	F 5037	27.33	9.60
4	Valul lui Traian	F 1 (5039)	32.60	5.82
5	Palas	F 5040	42.06	2.70
6	Constanta Cismea I	F 5041	4.21	0.57
7	Basarabi - capt	F 5042	18.00	9.82
8	Tortomanu	F 5044	33.00	8.80
9	Dunarea	F 5045	13.10	9.02
10	Pestera	F 5046	43.67	10.15
11	Castelu	F 5053	20.97	10.07
12	Baraganu	F 5060	77.63	16.75
13	Cernavoda	F 5061	14.30	12.01
14	Techirghiol	F 5069	15.50	14.01
15	Cumpana	F 5070	48.88	18.50
16	Medgidia - capt town	F 5091	22.45	-
17	Nazarcea capt.	F 1H	44.67	10.15
18	Nazarcea ISCIP	F 2	46.74	10.80
19	Rasova	F 2H	17.49	9.12
20	Lazu	F 8H	14.29	-
21	Ivrinezu Mare	F 1	13.72	11.10
22	Medgidia - capt town	F 1 (Car.)	13.28	9.81
23	Medgidia - SP Tortomanu	F 2	11.43	11.82
24	Valea Seaca	F 1	24.11	5.02
25	Medgidia - capt CT	P 0	16.11	11.68
26	Constanta	P 23	64.20	0.17
27	Constanta	P 24	43.06	1.42
28	Constanta Cismea I	P 25	15.92	0.12
29	North Constanta	P 26	11.94	0.83
30	North Constanta	P 27	3.22	0.41

Table 5.1. – Measurements in observation wells

The quality of groundwater confined to the lower aquifer complex may be disturbed especially in the southern areas where the aquifer is open level and locally allows direct interaction with the upper aquifer.

5.2. Hydrochemical elements of the karstic aquifers in the surveyed area

5.2.1. Groundwater quality evolution

The investigation of the evolution of groundwater quality in the area examined in this paper was based on the study of data collected from several time periods, both from the Sarmatian (upper) and the Jurassic - Cretaceous (lower) aquifers. However, for a more complete evaluation, water analyses from the Danube - Black Sea, respectively Poarta Albă - Midia, Năvodari waterways and from observation wells located in the vicinity of the waterways were taken into account.

The methods of sampling, sampling and analysis of water samples are presented in detail.

A set of analyses were carried out at the sampling points (in situ), while the rest of the analyses were carried out in specialized laboratories. The water samples transported to the laboratories are treated with chemical reagents, specific to each indicator, in order to preserve (to maintain) the water quality at the time of collection.

The following indicators can be determined in situ at the sampling points: temperature, dissolved oxygen, free carbon dioxide, pH, hydrogen sulphide, residual chlorine, organoleptic properties, bivalent iron.

5.2.1.1. Hydrochemical studies carried out on a regional scale in Southern Dobrogea between 1993 and 2015

In a first phase, the results of the analyses carried out on a regional scale in Southern Dobrogea between 1993 and 2015 were investigated. These studies revealed local contamination of the two aquifers (lower and upper) with chemicals. The main chemical indicators whose values exceeded the maximum permissible limits are nitrates (NO_3), chlorides (Cl^-) and ammonium (NH_4).

The results of the analyses obtained in 1996 were used for the author's preparation of two maps showing the spatial distribution of recorded contaminants exceeding the legal maximum allowable values in the two aquifers (the upper and the lower).

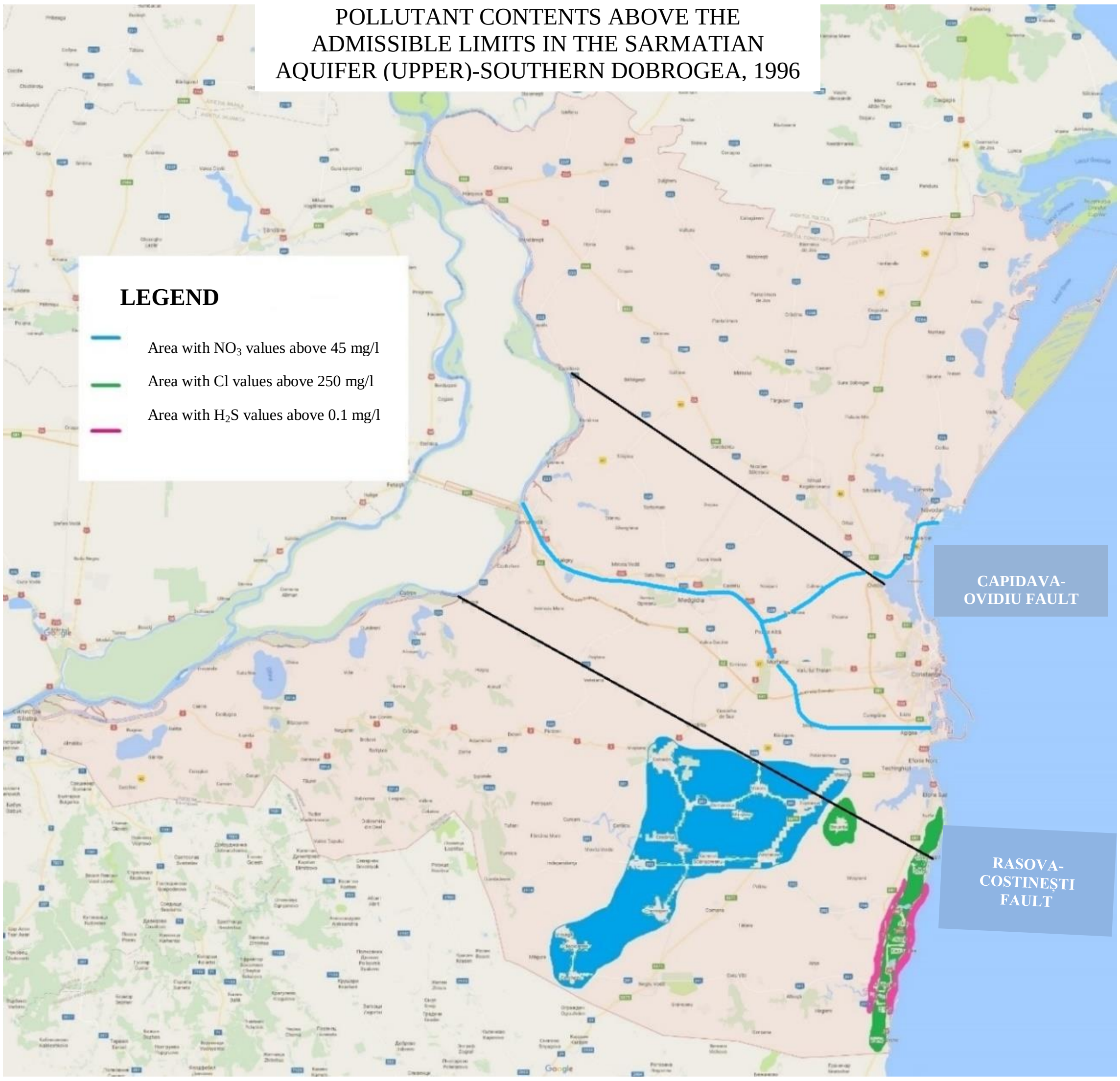


Figure 5.10. – Pollutant contents above permissible limits in the Sarmatian (upper) aquifer - Southern Dobrogea 1996 [43]

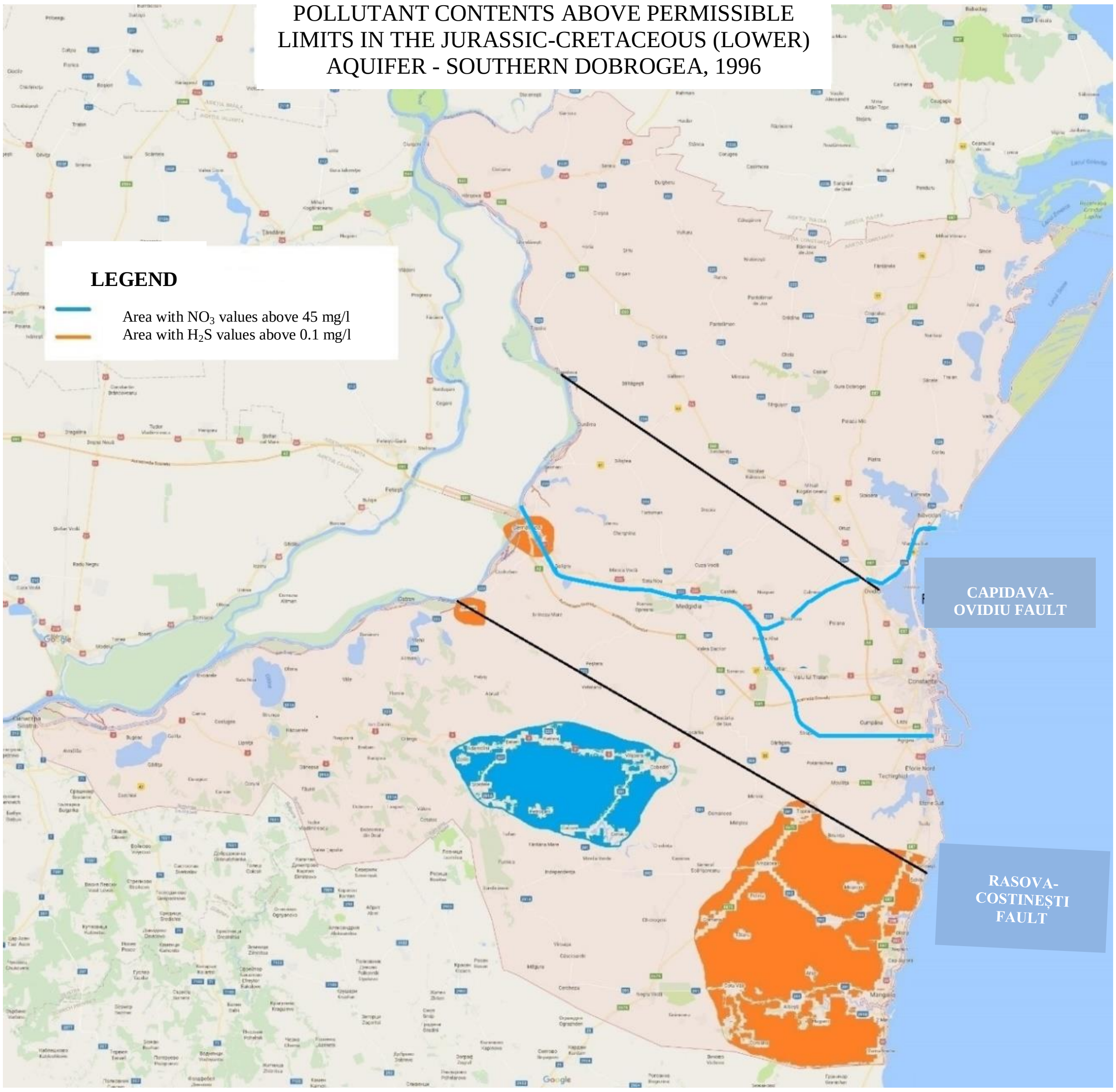


Figure 5.11. – Pollutant contents above permissible limits in the Jurassic - Cretaceous (lower) aquifer - Southern Dobrogea 1996 [43]

A measurement campaign was carried out in 2015 which revealed both an increase in nitrate concentrations and a wider spatial distribution in the upper (Sarmatian) aquifer. Thus, a massive presence of nitrate concentrations exceeding the legal permissible limits was recorded over large areas of southern Dobrogea.

5.2.1.2. Hydrochemical studies carried out in the surveyed area between 2000 and 2018

The study of the evolution of water quality in the area investigated in this work was carried out on the basis of physical-chemical and bacteriological analyses conducted by the water operator RAJA Constanta and the National Administration of Romanian Waters over a period of time from 2000 to 2018.

In order to determine the influences between the waterways and the main aquifers in the area as accurately as possible, both groundwater and surface water samples were taken and analysed from the following sites:

- water sampling points in waterways;
- observation wells located along waterways;
- Galesu water intake, located in the Poarta Albă - Midia, Năvodari waterway;
- groundwater sources in the vicinity of the waterways: Caragea Dermen, Murfatlar I, Murfatlar II, Medgidia Sud, Medgidia Nord.

The analysis bulletins of the water samples taken provided information on a wider range of physical-chemical parameters, but the evolution of parameters that may cause significant risks both for the environment (aquifer strata, waterways) and for the population's water consumption was analysed.

5.2.1.2.1. Water quality in surveyed waterways

From the analysis reports, it appears that the nitrate concentrations range from 1.57 to 14.59 mg/l in the Galesu water intake and from 0.09 to 10.88 mg/l in the Luminița sector - for the Poarta Albă - Midia, Năvodari waterway; respectively from 3.34 to 13.57 mg/l downstream of the Poarta Albă treatment plant - for the Danube - Black Sea waterway.

The resulting chloride concentrations ranged from 2.50 to 92.30 mg/l in the Galesu water intake and from 35.5 to 316.0 mg/l in the Luminița sector - for the Poarta Albă - Midia Năvodari waterway and from 14.4 to 106.5 mg/l downstream of the Poarta Albă treatment plant - for the Danube - Black Sea waterway.

Ammonium concentrations ranged from 0.037 to 0.267 mg/l in the Galesu water intake and from 0.010 to 0.458 mg/l in the Luminița sector - for the Poarta Albă - Midia, Năvodari waterway and from 0.015 to 0.78 mg/l downstream of the Poarta Albă wastewater treatment plant - for the Danube - Black Sea waterway.

The pH values are between 7.23 - 8.76 in the Galeșu water intake and between 7.05 - 9.10 in the Luminița sector - for the Poarta Albă - Midia, Năvodari waterway; respectively between 7.11 - 8.74 downstream of the Poarta Albă treatment plant - for the Danube - Black Sea waterway.

The water quality in terms of the parameters analysed in the time period 2010 - 2018 is generally within the legally admissible limits. In two out of the three water sampling points, the concentrations of chlorides and ammonium were found to be above the legal limits.

Downstream of the Poarta Albă wastewater treatment plant, in the Danube - Black Sea waterway, an exceedance of ammonium concentration above the legal permissible limit was observed (0.78 mg/l - March 2015), as shown in Figure 5.12. (Pollution source WWTP Poarta Albă).

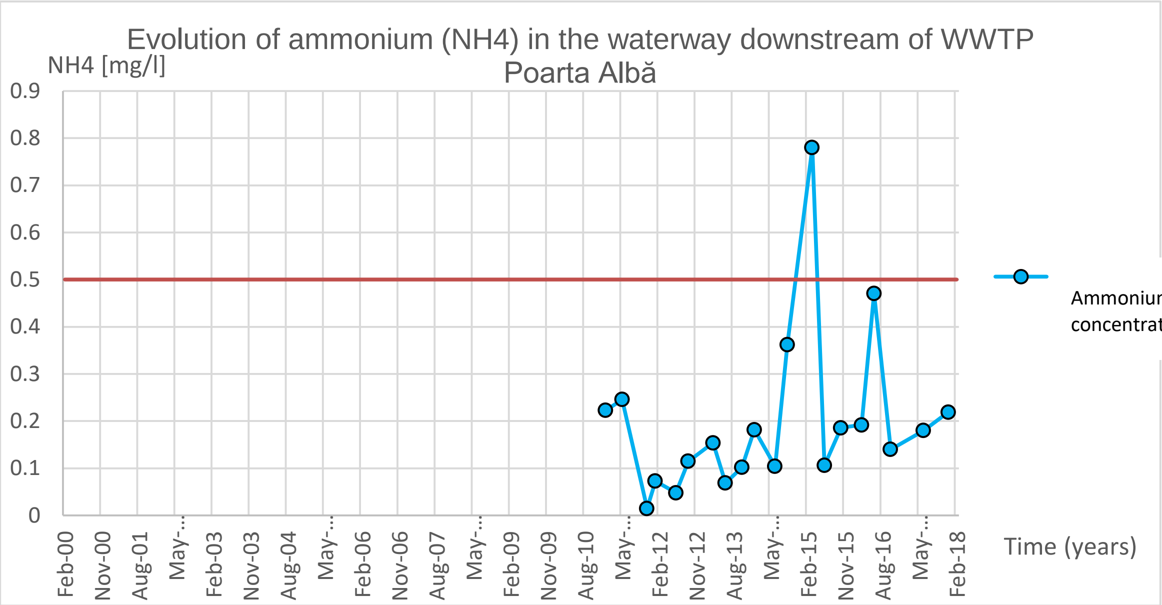


Figure 5.12. – Evolution of ammonium concentrations downstream WWTP Poarta Albă - D.M.N. waterway (ANAR analysis)

In the Poarta Albă - Midia, Năvodari waterway, in the Luminița sector, successive exceedances of chloride concentration above the legal admissible limit were observed (the source being the lock).

5.2.1.2.2. Water quality in the Galesu water intake of the Poarta Albă – Midia, Năvodari waterway

The Galeșu water intake (Q=4.5 mc/s) is located in the Poarta Albă - Midia, Năvodari waterway at km. 6+398.

In general, the parameters analysed are within the legally permissible limits. However, there was one event in June 2014 in which the ammonium concentration (1,131 mg/l) exceeded the legal permissible limit.

5.2.1.2.3. Water quality in groundwater sources in the vicinity of waterways

The assessment of water quality in groundwater sources located in the vicinity of the Danube - Black Sea, respectively Poarta Albă - Midia, Năvodari waterways was carried out on the basis of physical-chemical analyses performed by the water operator RAJA Constanța.

The synthesis of the information obtained from the analysis bulletins carried out both by the water operator RAJA Constanta and by the National Administration of Romanian Waters in the time interval 2000 - 2018 is presented in Table 5.2. below. This table shows the evolution of groundwater quality in the Jurassic - Cretaceous (lower) aquifer for the four analysed parameters:

Jurassic - Cretaceous aquifer (lower).	
NO_3^-	Nitrate concentration values from the taken underground and surface water samples are generally below the maximum legally permissible values. There are a few exceptions where exceedances of nitrate concentrations above the legal limits were detected (Caragea Dermen - 110.60 mg/l in 2003 and Murfatlar I - 50.40 mg/l in 2008 and 70.40 mg/l in 2012).
Cl^-	From the analyzes carried out, in general the values of chloride concentrations from the samples of underground and surface water taken are below the maximum legally permissible values, there being no exceedances. The presence of chloride concentrations above the legal limits is observed, especially in the coastal areas, in the Poarta Albă - Midia, Năvodari waterway in the Luminiţa sector and in the Agigea observation well, in the vicinity of the Danube - Black Sea waterway, due to the occurrence of the sluice phenomenon.
NH_4^+	Broadly speaking, the recorded ammonium concentration values fell within the legally admissible limits. However, isolated events were detected, in which the legally admissible limits were exceeded in the Danube - Black Sea waterway, downstream of the Poarta Albă wastewater treatment plant (0.78 mg/l in March 2015); in the observation well Straja (3.315 mg/l in May 2015) located on the route of the Danube - Black Sea waterway and in the Poarta Albă - Midia, Năvodari waterway in the Galesu water intake (1.131 mg/l in June 2014).
pH	The pH values have an evolution between the legally admissible values, and there is no exceedances for any of the analyzed water samples.

Table 5.2. – The synthesis of the results obtained between 2000-2018

5.2.2 Qualitative inteaction of waterways with aquifers.

Through the analyses, information was obtained regarding the quality of the water samples taken over a period of 18 years, between 2000 and 2018. At the same time, correlations were made between the results of the analyzes carried out in the waterways, the observation wells located adjacent and underground catchments exploiting the lower aquifer (Jurassic – Cretaceous).

5.2.2.1 Danube – Black Sea waterway

An event has been recorded in March 2015, when insufficiently purified water discharged into the waterway caused an exceedance of the ammonium concentration (0.78 mg/l) above the legally permissible limit. Pollutant transport phenomena contributed to pollutant movement and dissolution in waterway water. In the observation well Straja, located on the right bank of the waterway, a significant increase in the concentration of ammonium (3.315 mg/l), well above the legally admissible limit, was detected in May 2015. Correlating these results, it is observed that the pollutant traveled a distance of about 14 km through the waterway to the Straja observation drill in a time span of about 2.5 months.

During this period (March – May 2015) in the Murfatlar I and II catchments, which exploit the lower Jurassic-Cretaceous aquifer and are located on both banks of the Danube-Black Sea waterway, between Poarta Albă and Straja, no increases in ammonium concentration were recorded.

That means that the pollutant source was felt locally only in the waters of the waterway and adjacent to it, in the phreatic (surface) layers, not affecting the quality of the water in the lower aquifer.

5.2.2.2 Poarta Albă – Midia, Năvodari waterway

On a section between the Ovidiu lock and 3 km upstream from it, the waterway is excavated in the reseervoir rocks of the lower Jurassic-Cretaceous aquifer.

In conclusion, the qualitative interaction between the waters of the Poarta Albă - Midia, Năvodari waterway and the aquifer layers are generally manifested locally, on the section between the Ovidiu lock and up to the discharge into the Black Sea. In case of an accidental pollution on the section between Poarta Albă and Ovidiu Lock, there is a risk of contamination for the lower Jurassic-Cretaceous aquifer in the area where the waterway is excavated in the reservoir rock. Under certain conditions, this can have serious consequences for the water sources that exploit the lower aquifer.

5.3 The main underground sources of the investigated areas.

5.3.1 Vulnerable groundwater sources

- Groundwater sources of Constanța municipality

Constanta Municipality has four underground intakes, located south of the Poarta Albă – Midia, Năvodari waterway namely: Caragea Dermen, Cișmea I, Cișmea II and Constanța Nord.

During the execution period of the Poarta Albă - Midia, Năvodari waterway (1983 - 1988), the underground catchments of the municipality of Constanța benefited from 75 wells and exploited strata with depths between 25 and 300 m. The exploitation regime of the catchments was determined by the seasonal nature of water consumption, which meant large variations between summer and winter. In total, these catchments provided an average annual flow of approximately 3000 l/s.

The decrease in piezometric levels in the entire researched area in 1987 represents the effect of the insufficient restoration of the aquifer in the period of November 1987 - February 1988, after a period of intense demand (March - October 1987), when average monthly flows were extracted from all the catchments of the municipality of Constanța over 4000 l/s.

At the regional level, the piezometric load imposed in a first phase by the depletion works carried out during execution and later after the waterway was put into operation (water level in the waterway +7.5 m, upstream of the Ovidiu lock) significantly influenced and hydrostatic levels in the Jurassic-Cretaceous (lower) aquifer. After commissioning, the waterway represented a supply source for the lower aquifer on a section of approximately 3 km, located upstream of the Ovidiu lock.

❖ The water sources of the city of Murfatlar (Basarabi)

The Murfatlar I and II water sources (formerly Basarabi) are located in the Carasu valley, between the towns of Basarabi and Porta Albă, on both banks of the Danube - Black Sea waterway. The two sources were initially sized to ensure a capture capacity of approximately Q = 900 l/s, and currently provide 532 l/s, which provides the water needs for the Murfatlar, Poarta Albă and Galeșu localities.

Over time, it was found that two factors intervened in the operation of the Murfatlar catchment that influenced the hydrodynamic and quality conditions of the underground water:

- the construction of the main irrigation canal between the Poarta Albă pumping station and the Basarabi - forest pumping station, put into operation in 1970;

- the execution of the Danube - Black Sea waterway felt more strongly in the period 1980 - 1983 and its commissioning after 1983.

After the waterway started working, the hydrostatic levels registered a gradual increase in the phreatic aquifer, up to +7.00 m. with depths between 60 - 150 m, to exploit in a major proportion the Jurassic-Cretaceous (lower) aquifer.

Although Senonian chalk deposits are found between the two aquifers, the phreatic and the lower, which usually stop the communication between the aquifers, under certain conditions, in which high flows are exploited and the piezometric levels decrease, the phenomenon of downward vertical drainage occurs.

5.3.2 Safe underground water sources in operation

❖ The North of Medgidia water source

In 1987, this water source was put into operation consisting of 12 wells drilled at depths of 350-500 m (Q = 1000 l/s). To eliminate the risks of pollution, the first 150 m of the drilling were provided with a definitive column cemented behind, and from this depth to the bottom of the drill, a free hole remained in limestone and dolomite.

Currently, two of the exploitation wells have been connected to the new water supply for the city of Cernavodă, which thus benefits from chemical and bacteriological stable drinking water.

An exploitation well was connected to the water supply system of the municipality of Medgidia to take over the consumption peaks of the summer season.

Given the fact that the water sources of the coastal towns in the south of the county have suffered serious contamination due to polluting substances from agriculture, the water operator RAJA Constanța has taken the decision to introduce into the investment program the use of nine exploitation wells, from the North of Medgidia catchment, to ensure the consumption of drinking water.

6 NUMERICAL MODELLING ON A STUDY CASE

Numerical modeling carried out by means of calculation programs is a useful tool in studying and evaluating underground aquifer systems, as well as in designing and increasing the operational efficiency of both underground water resources and various hydrotechnical constructions.

Any natural case analyzed can be conceptualized, by simplifying the natural system and adopting some hypotheses, which simulate the case as closely as possible to the real one. The degree of accuracy of the results obtained is directly proportional to the degree of accuracy of the data and assumptions entered into the numerical model.

6.1 Model representation

The conceptual model built in this work was intended to be used for the research of the Jurassic - Lower Cretaceous karst aquifer, present in the studied area, Constanța county, Romania.

The studied area is located in the north of South Dobrogea, in the region between the Capidava – Ovidiu and Rasova – Costinești faults, the Danube river and the Black Sea (according to Figure 4.1. - Situation plan of the researched area).

The perimeter of the studied area has the following plan geometry: 68 km - length, respectively 32 km - width. The entire surface of the model was discretized in a grid of cells with variable sizes according to the analyzed areas of interest. Thus, the horizontal dimensions of the discretization cells are generally 1000 m x 1000 m, but a finer discretization of 500 m x 500 m is noted in areas with underground catchments, for higher accuracy of results. The heights of the discretization cells are equal to the thicknesses of the lower Jurassic-Cretaceous aquifer, intercepted in the wells, and are between 12.80 m and -1205.33 m.

The construction of the flow model of the lower Jurassic-Cretaceous aquifer was achived by entering lithological data, boundary conditions, observation drillings conditions, observation drillings and capture drillings into the calculation program.

Lithology of the lower Jurassic-Cretaceous aquifer was determined by interpolation, using the aquifer thicknesses detected in each observation well as basic data.

The boundary conditions imposed for the creation of the flow model were determined by interpolation, based on the piezometric map of the lower Jurassic-Cretaceous aquifer. [28] Boundary conditions of the imposed load type were introduced into the numerical model, presented synthetically in table 6.1. presented below. The Northern border of the model, represented by the Capidava – Ovidiu fault, was considered to be a sealed border. Also, both the Siutghiol lake and the Poarta Albă – Midia, Năvodari waterway, which is in direct contact with the Jurassic – Cretaceous lower aquifer, were imposed an imposed potential type load of +1.25 m. At the same time, upstream of the Ovidiu lock, on a section of approximately 3 km of the waterway, a potential load of +7.50 m was imposed.

Nr. Crt.	Fronieră	Tronson	Lungime [m]	Tip potențial	Potențial impus
1	Nordică	-	-	etansa	-
2	Vestică	1 - 2	4234	variabil	9.2 - 9.0
		2 - 3	7076	liniar	9
		3 - 4	3244	variabil	9 - 12
		4 - 5	6640	liniar	12
		5 - 6	2448	variabil	12 - 10
		6 - 7	3528	variabil	10 - 9.5
		7 - 8	8702	variabil	9.5 - 9
3	Sudică	8 - 9	3230	variabil	9 - 10
		9 - 10	1802	variabil	10 - 11
		10 - 11	2750	variabil	11 - 12
		11 - 12	6282	variabil	12 - 11.5
		12 - 13	7156	variabil	11.5 - 12
		13 - 14	10032	variabil	12 - 19
		14 - 15	8808	variabil	19 - 21
		15 - 16	27278	variabil	21 - 18.7
4	Estică	16 - 17	16242	variabil	18.7 - 18
		17 - 18	718	liniar	18
		18 - 19	4802	variabil	18 - 11
		19 - 20	18670	variabil	1 - (-1)
		20 - 21	1062	liniar	0
5	lac Siutghiol			liniar	1.25
6	sector 3 km amonte ecluza Ovidiu - canal PAMN		3000	liniar	1.25

Table 6.1. *– Imposed boundary conditions*

The date of the observation drillings located in the studied area are centralized in table 6.2.

The in-plane coordinates (x, y) for each observation wells were determined by means of a local coordinate system located as follows:

- The source of the system is on the Danube river, to the South-West of the Rasova town.
- The Ox axis is located in the direction of the Rasova – Costinești fault;
- Axa Oy is located in the direction of the Danube river.

The hydrostatic levels in the observation drillings were determined following the measurements made in 2018.

Nr. Crt.	Locality	Wells	Coordonate locale (model)		Cota teren	NHs (2018)
			x [m]	y [m]	[m]	Cote [m]
1	Basarabi (Murfatlar)	F 5035	37099.7666	13297.7436	15.88	7.1
2	Poarta Alba	F 5036	36537.8339	18090.6771	23.07	13.15
3	Poarta Alba	F 5037	37556.9580	19075.2914	27.33	9.6
4	Valul lui Traian	F 1 (5039)	42984.6574	15528.7713	32.60	5.82
5	Palas	F 5040	47493.1840	18578.3388	42.06	2.7
6	Constanta Cismea I	F 5041	49111.6481	26373.5305	4.21	0.57
7	Basarabi - capt	F 5042	36200.4523	14975.6964	18.00	9.82
8	Tortomanu	F 5044	15104.7347	21323.5673	33.00	8.80
9	Dunarea	F 5045	1450.8971	26676.9677	13.10	9.02
10	Pestera	F 5046	18142.6074	2535.9964	43.67	10.15
11	Castelu	F 5053	26773.8997	20373.3085	20.97	10.07
12	Baraganu	F 5060	41266.8374	6212.6580	77.63	16.75
13	Cernavoda	F 5061	1090.6785	14058.5439	14.30	12.01
14	Techirghiol	F 5069	56808.4853	11582.8823	15.50	14.01
15	Cumpana	F 5070	51621.6116	13809.2180	48.88	18.5
16	Medgidia - capt oras	F 5091	23417.9633	15069.3299	22.45	-
17	Nazarcea capt.	F 1H	35353.2144	21151.8841	44.67	10.15
18	Nazarcea ISCIP	F 2	35160.0076	20717.7792	46.74	10.8
19	Rasova	F 2H	1255.5474	1255.5474	17.49	9.12
20	Lazu	F 8H	54878.5903	16583.3787	14.29	-
21	Ivrinezu Mare	F 1	9328.8705	4165.0696	13.72	11.1
22	Medgidia - capt oras	F 1 (Car.)	24450.7068	15561.6760	13.28	9.81
23	Medgidia - SP Tortomanu	F 2	23698.4415	16915.4534	11.43	11.82
24	Valea Seaca	F 1	40934.3303	15499.6499	24.11	5.02
25	Medgidia - capt CT	P 0	23145.1936	15675.1893	16.11	11.68
26	Constanta	P 23	49711.2935	23106.0808	64.20	0.17
27	Constanta	P 24	49379.4343	24512.7633	43.06	1.42
28	Constanta Cismea I	P 25	49340.3607	25701.3087	15.92	0.12
29	Constanta Nord	P 26	49462.7947	27715.9392	11.94	0.83
30	Constanta Nord	P 27	49714.5058	28109.8365	3.22	0.41

Table 6.2. – Observation wells in the studied area

The values of the average flow rates exploited from the underground water intakes located in the areas adjacent to the waterways, which supply the municipality of Constanța, the cities of Medgidia, Murfatlar and the commune of Valul lui Traian are presented in table 6.4. and were provided by the water operator RAJA Constanța.

Nr. Crt.	Captare de apă	Debit exploatat	
		[mc/zi]	[l/s]
1	Caragea Dermen	55119.74	637.96
2	Cișmea I	133505.97	1545.208
3	Cișmea II	29926.20	346.368
4	Constanța Nord	18066.24	209.1
5	Basarabi I	39391.49	455.92
6	Basarabi II	6092.93	70.52
7	Valul lui Traian	16321.00	188.9
8	Medgidia oraș	38880.00	450
9	Medgidia pentru oraș Constanța	17280.00	200

Table 6.3. –Exploited flow from underground catchments

6.2 The model used

The construction of the calculus model of the studied area and the numerical simulations for different flow scenarios were carried out using the GMS software package.

This model was created to evaluate the interaction between Danube - Black Sea, respectively Poarta Albă - Midia, Năvodari waterways with underground water sources, located in fissural - karst aquifers.

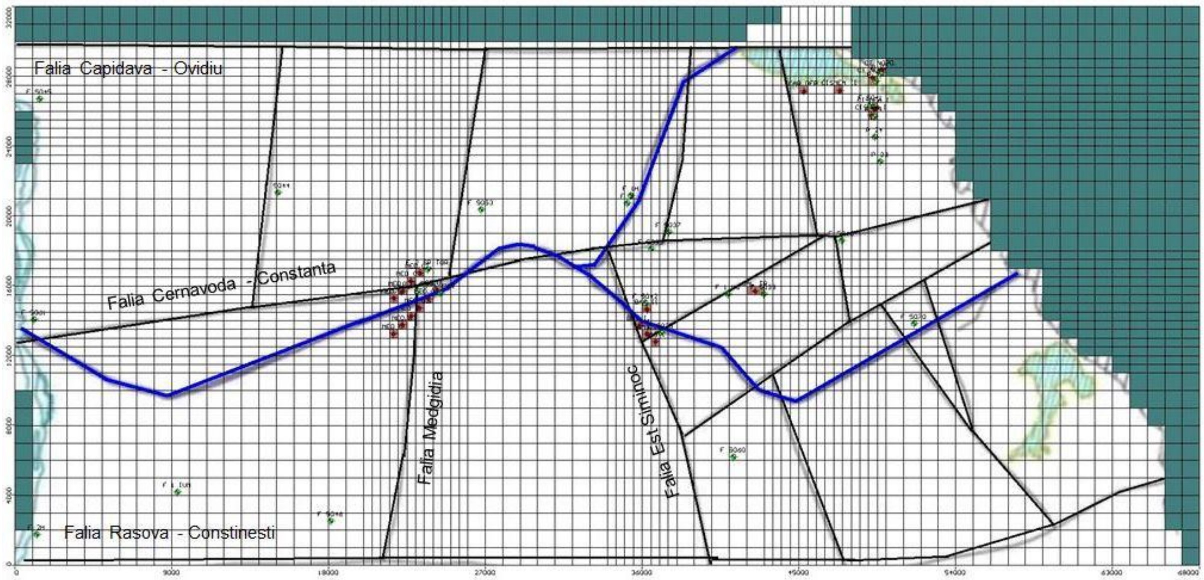


***Figure 6.1.* –** Jurassic – Cretaceous lower aquifer regional model

6.3 Grid of the studied model

The lithology of the studied aquifer (Jurassic – Cretaceous) was created by the GMS program, by interpolation, after entering the thickness of the aquifer in each observation drillings. The figures below show two horizontal and vertical cross-sections of the lower Jurassic-Cretaceous aquifer created by the program.

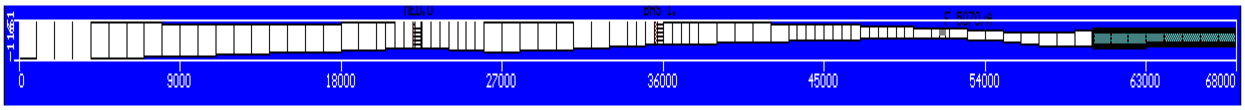


***Figure 6.2.* –** Horizontal section 1 through the regional model grid

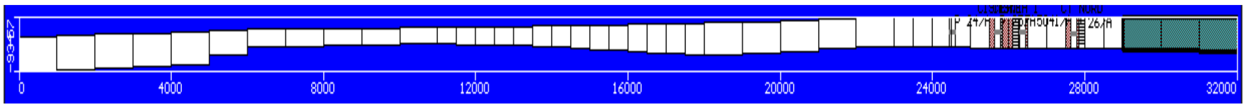


***Figure 6.3.* –** Vertical section 1 through the regional model grid

6.4 Model calibration

The calibration of the flow model was carried out in stationary mode, based on the elevations of hydrostatic levels from observation wells, measured in 2018. The boundary conditions used were of imposed load and imposed flow type. The imposed load type conditions were established by interpolation based on the piezometric map of the lower Jurassic-Cretaceous aquifer, while for the imposed flow type conditions, the data provided by the RAJA Constanța water operator were used. The water level quotas in the Danube - Black Sea, respectively Poarta Albă - Midia, Năvodari waterways have different values depending on the tributaries, according with the provisions of the operation and maintenance regulations of the waterways.

Boundary conditions of imposed flow type refer to the flows captured from the lower aquifer. In the numerical model the catchments of the cities of Constanța, Murfatlar and Medgidia, but also the catchment of Valu lui Traian commune were represented by the pumping wells from which various flows are extracted (figure 6.1.).

The process of calibrating the model was carried out by the method of successive tests, by adjusting the values of hydraulic conductivities until the calculated levels in all observation drillings were close to the measured levels. [27]

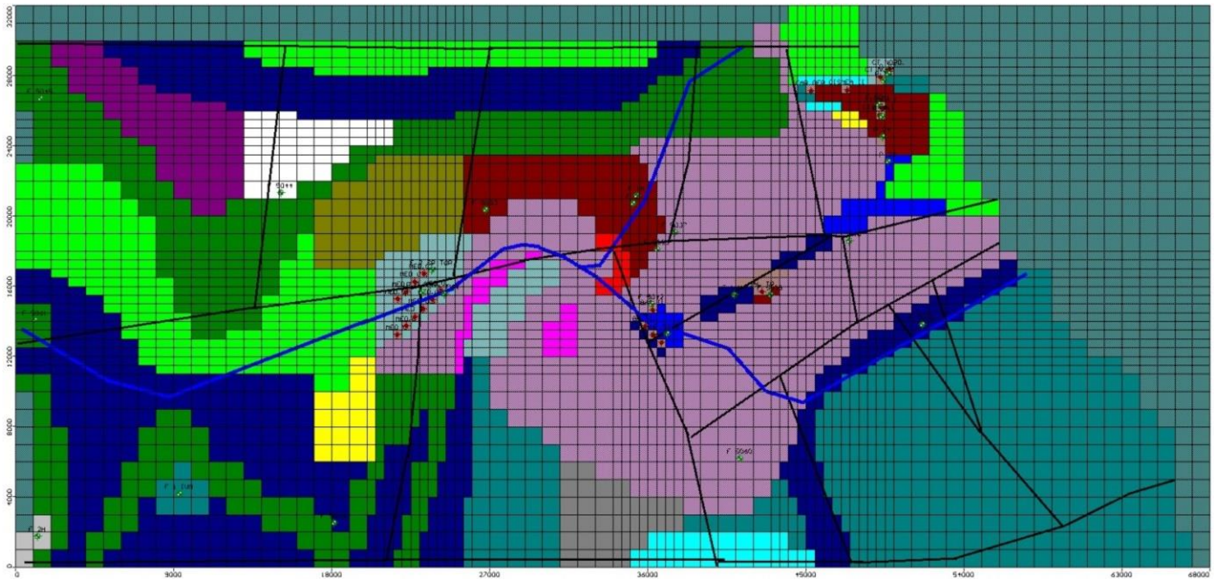
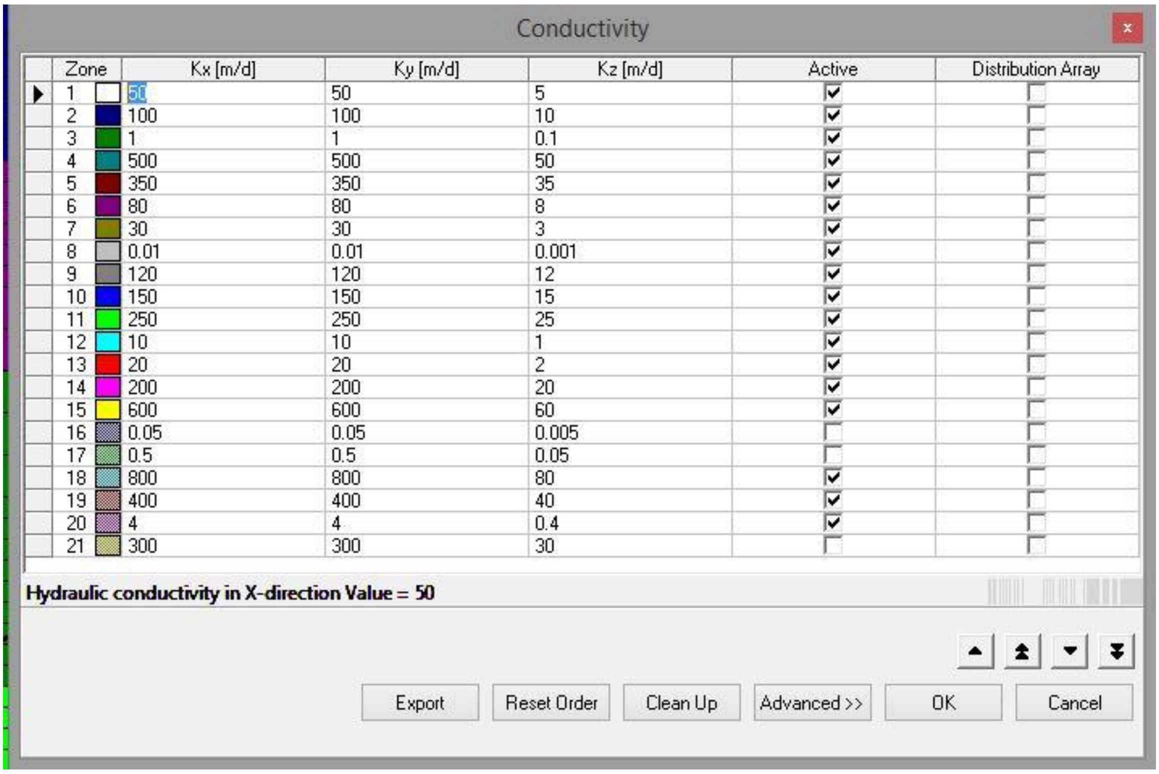


***Figure 6.4.* –** Distribution of hydraulic conductivities used for regional model calibration



Conductivity

Zone	Kx [m/d]	Ky [m/d]	Kz [m/d]	Active	Distribution Array
1	50	50	5	☑	☐
2	100	100	10	☑	☐
3	1	1	0.1	☑	☐
4	500	500	50	☑	☐
5	350	350	35	☑	☐
6	80	80	8	☑	☐
7	30	30	3	☑	☐
8	0.01	0.01	0.001	☑	☐
9	120	120	12	☑	☐
10	150	150	15	☑	☐
11	250	250	25	☑	☐
12	10	10	1	☑	☐
13	20	20	2	☑	☐
14	200	200	20	☑	☐
15	600	600	60	☑	☐
16	0.05	0.05	0.005	☐	☐
17	0.5	0.5	0.05	☐	☐
18	800	800	80	☑	☐
19	400	400	40	☑	☐
20	4	4	0.4	☑	☐
21	300	300	30	☐	☐

Hydraulic conductivity in X-direction Value = 50

Export | Reset Order | Clean Up | Advanced >> | OK | Cancel

***Figure 6.5.* –** Hydraulic conductivities values used for regional model calibration

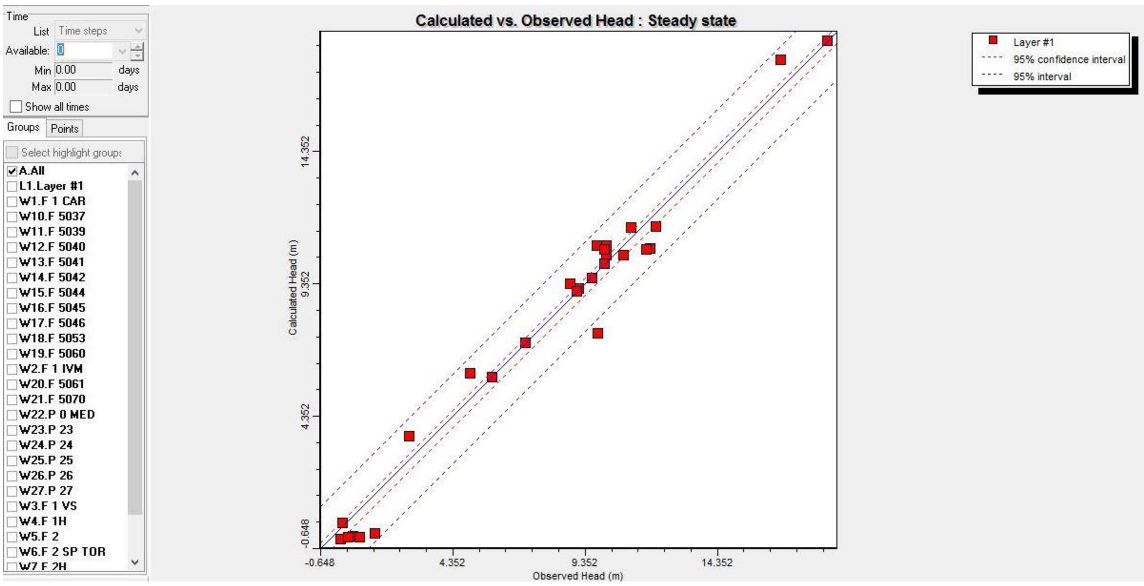


***Figure 6.6.* –** Graph of calculated levels vs measured levels in the observation wells following model calibration

In general, a numerical model is considered to be well calibrated if the difference between the calculated and measured levels in all observation wells is at most 1.0 m. [27] For this model, larger differences of 1.0 m, between the calculated and measured levels, in two observation drillings (F 5042 Basarabi – 2.33 m and F 24 Constanța – 1.47 m). However, given that this model was created for research purposes, at a regional scale (68,000 m x 32,000 m), and some measurements may have small uncertainties, the model can be considered calibrated. After the model calibration process, resulted in the distribution of the hydraulic conductivities of the aquifer (figure 6.4.), whose values are between 0.01 m/day, locally, in a sector around the F 2H Rasova well and 800 m/day in the Medgidia city area, mainly in the area of the catchment fronts Medgidia city, respectively the North of Medgidia for the city of Constanța. The high values of the hydraulic conductivities in the researched area indicate the idea that the lower karst fissure aquifer presents strongly karstified sectors, with large underground voids. The system of vertical and horizontal faults in the analyzed area generated a series of uneven tectonic blocks in terms of hydraulic conductivity.

6.5 Study case

After the completion of the the calibration and the running process of the regional model, the result was the hydrodynamic map of the Jurassic-Cretaceous lower aquifer, presented in figure 6.7.

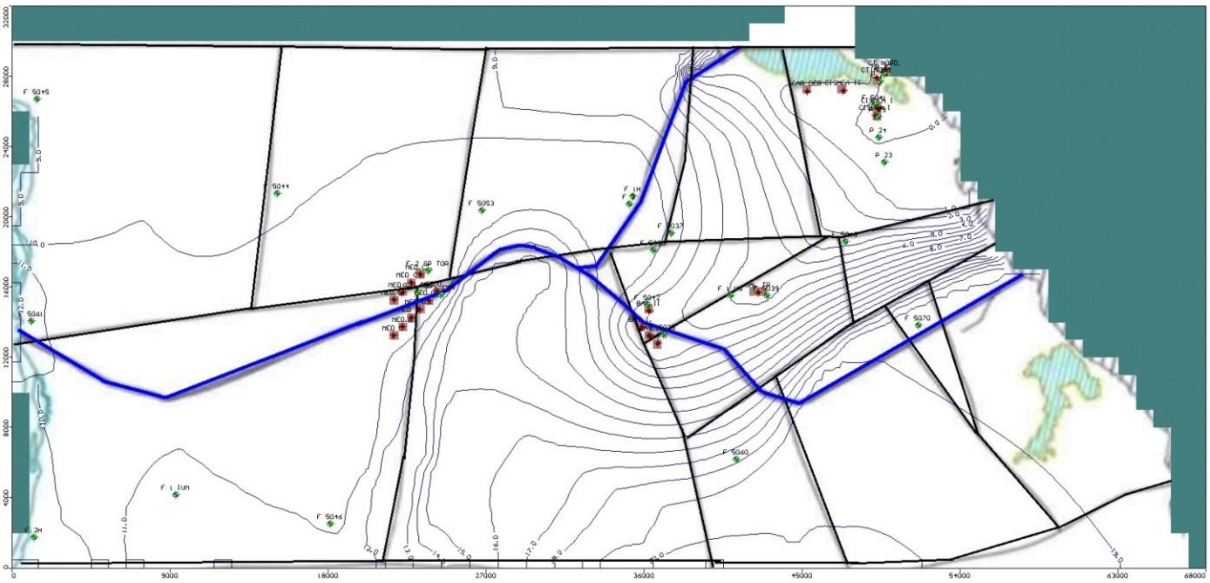


Figure 6.7. **–** Hydrodynamic map of the calibrated regional model

The program also generated the flow directions through the calibrated regional model and the catchment well supply areas.

The flow directions resulting from the calibration are predominantly oriented South-West - North-East, according to figure 6.10. Locally, in the area bounded by the Lazu – Cumpăna and Cernavodă – Constanța faults, the hydraulic conductivities have low values, and the flow directions are oriented South – North. North of the Cernavodă-Constanța fault, they return to the Southwest-Northeast flow directions.

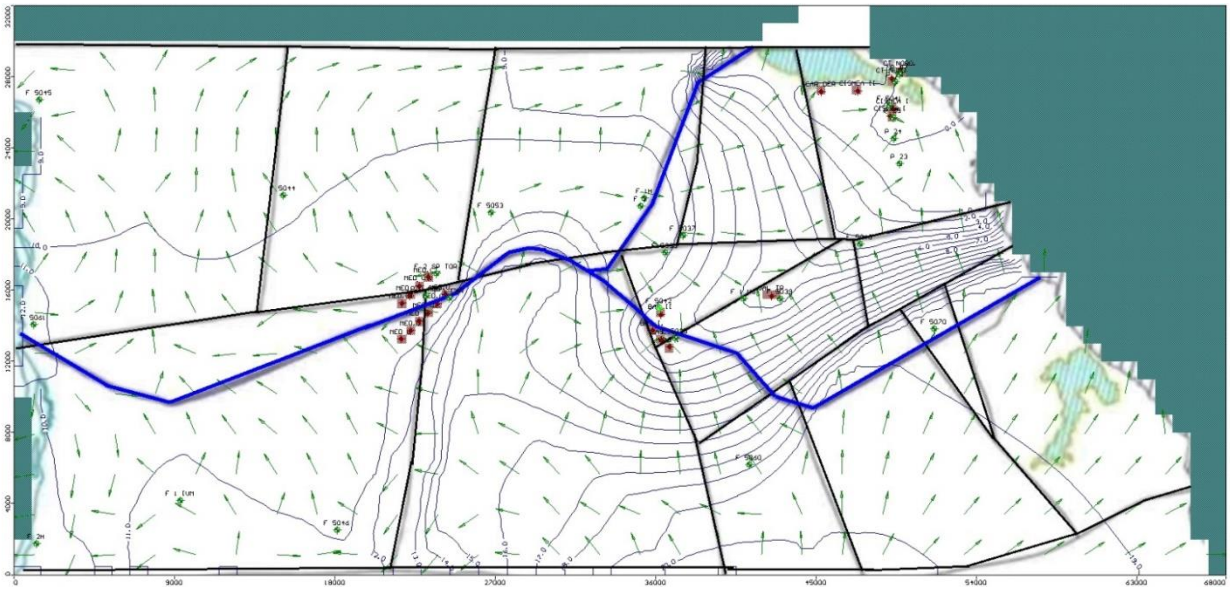


Figure 6.8. – Flow directions through the calibrated regional model

In the area of the Ovidiu lock, in the Poarta Albă - Midia, Năvodari waterway, a local disturbance was observed, determined by the direct hydraulic connection between the water in the waterway and the aquifer. At the same time, disturbances were observed in the catchment areas of the municipality of Constanța, Murfatlar, Valul Lui Traian and Medgidia.

In figure 6.8. it can be seen that most of the catchment wells are recharged from the southern border of the domain, with the exception of the wells from the North of Constanța, Cismea II and partially Cismea I catchments, which are powered from the northern border and sometimes from Lake Siutghiol.

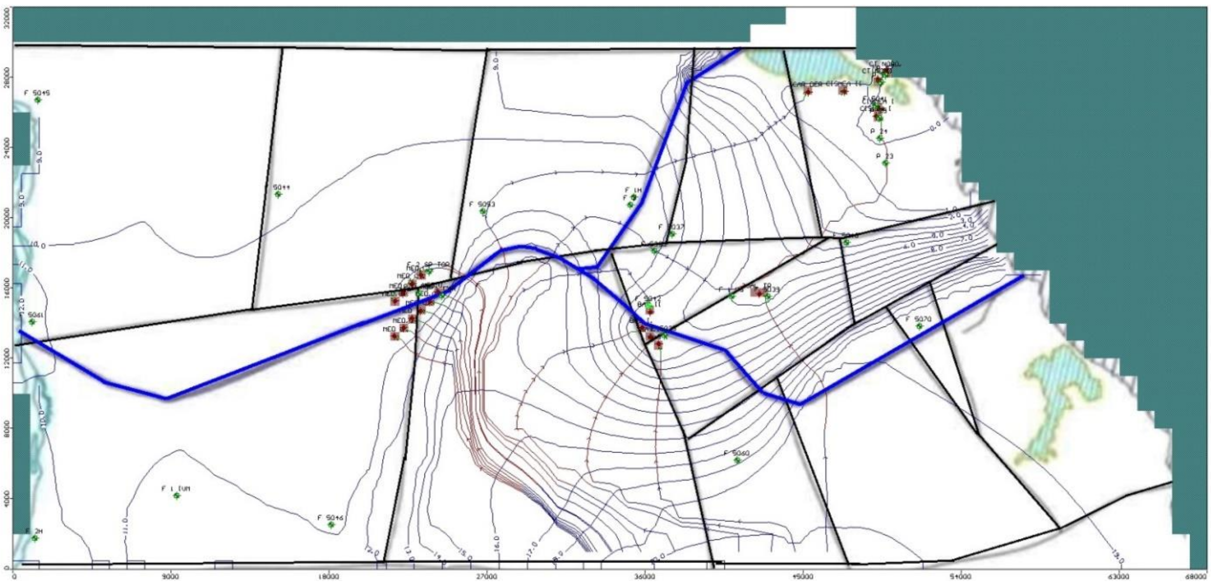


Figure 6.9. – Supply areas of catchment wells

According to figure 6.9., if the possibility of contamination of the lower aquifer is studied and the hypothesis of an advective pollutant transport is adopted, i.e. the movement of the pollutant is carried out only as a result of its entrainment by the water flow, the model shows that there is currently no danger of contamination collection drillings with water from the Poarta Albă - Midia, Năvodari waterway.

According to the calibrated regional model, certain areas were drawn on the eastern, southern and western borders to create a debit balance.

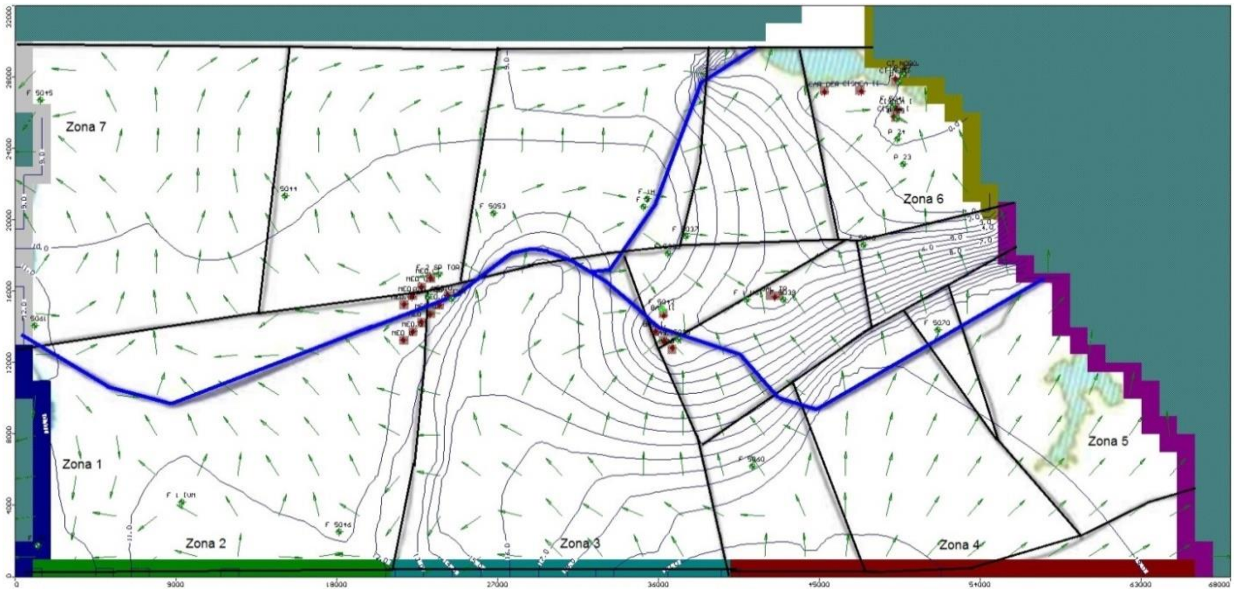


Figure 6.10. **–** Delimited areas for flow balance

Nr. Crt.	Fronieră	Intrare mc/zi	Iesire mc/zi
1	lac Siutghiol + tronson canal PAMN (ecluza Ovidiu - 3 km amonte)	91180	21014
2	Captari	0	345550
3	Zona 1	75296	10133
4	Zona 2	39667	53862
5	Zona 3	483650	348500
6	Zona 4	474800	0
7	Zona 5	12840	366340
8	Zona 6	152160	939070
9	Zona 7	287610	353520

Table 6.4. **–** Flow balance of the calibrated regional model

The calibrated regional model was used to simulate three hypotheses:

- hypothesis 1: the increase of flows captured from the catchments of the municipality of Constanța from 2740 l/s (currently) to 4000 l/s;

- hypothesis 2: polluant transport from the area upstream of the Ovidiu lock;

- hypothesis 3: the proposal of two underground catchments in the localities of Ivrinezu Mare and Peștera.

6.5.1 Hypothesis 1 – Increased flow

Due to the fact that in the summer period, water consumption is very high in the coastal area, and the flows exploited from the catchments of the municipality of Constanța can reach very high values, the behavior of the lower Jurassic-Cretaceous aquifer was followed in the case of exploitation with high values of flows. Thus, it was imposed that the sum of the flows extracted from the Caragea Dermen, Cismea I, Cismea II, Constanța Nord catchments should reach 4000 l/s, compared to the currently exploited flows, which add up to approximately 2740 l/s.

After applying hypothesis 1 and running the model, the hydrodynamic map of the lower Jurassic-Cretaceous aquifer resulted, shown in figure 6.11.

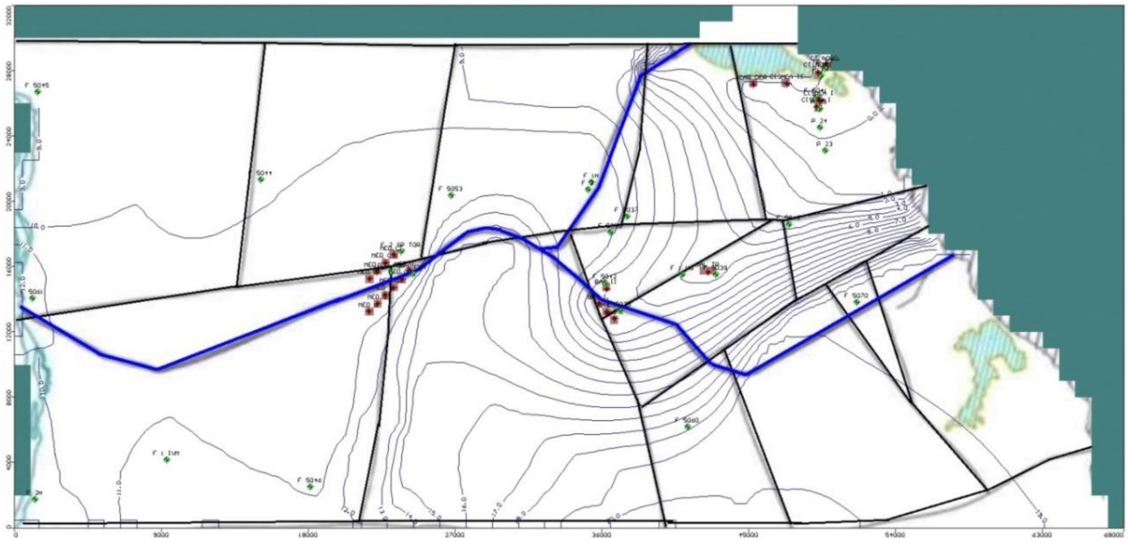


Figure 6.11. **–** Hydrodynamic map of the model after the simulation of hypothesis 1

The flow directions resulting from running the model with assumption 1 have the same orientations as those resulting from the calibrated model simulation.

The supply areas of the capture wells resulting from running the model with hypothesis 1 are identical to those resulting from the simulation of the calibrated model.

The debit balance resulting from running the model with hypothesis 1 is presented below:

Nr. Crt.	Fronieră	Intrare mc/zi	Iesire mc/zi
1	lac Siutghiol + tronson canal PAMN (ecluza Ovidiu - 3 km amonte)	961330	20911
2	Captari	0	450420
3	Zona 1	75322	10129
4	Zona 2	39675	53843
5	Zona 3	483710	348450
6	Zona 4	474880	0
7	Zona 5	12852	366280
8	Zona 6	172540	904470
9	Zona 7	287650	353450

Table 6.5. – Flow balance of the regional model after the simulation of hypothesis 1

6.5.2 Hypothesis 2 – Pollutant transport

The developed regional numerical model was further used for the simulation of pollutant transport, also taking dispersion into account. Several scenarios of accidental pollution were simulated, in which a pollutant was introduced into the area of the Ovidiu lock, from the Poarta Albă - Midia waterway, Năvodari. The pollutant transport simulations were carried out in this area because on the section between the Ovidiu lock, respectively 3 km upstream on the Poarta Albă - Midia, Năvodari waterway, the Jurassic - Cretaceous lower aquifer is in direct contact with the waters of the waterway. The simulations were made for a maximum period of 30 years, considering the quasi-stationary flow regime, while the exploitation flows from the underground catchments had both a variant with the values provided by the operator RAJA Constanța, and another variant with the values calculated for a total flow exploited from the sources of the Municipality of Constanța (according to hypothesis 1) of 4000 l/s. The investigated pollutant had a concentration of 100 mg/l, while the dispersivity of the medium was varied.

The results of pollutant transport simulations for the calibrated model are presented at different exposure times: after 10 days, after 1 year, after 10 years and figure 6.12 - after 30 years.

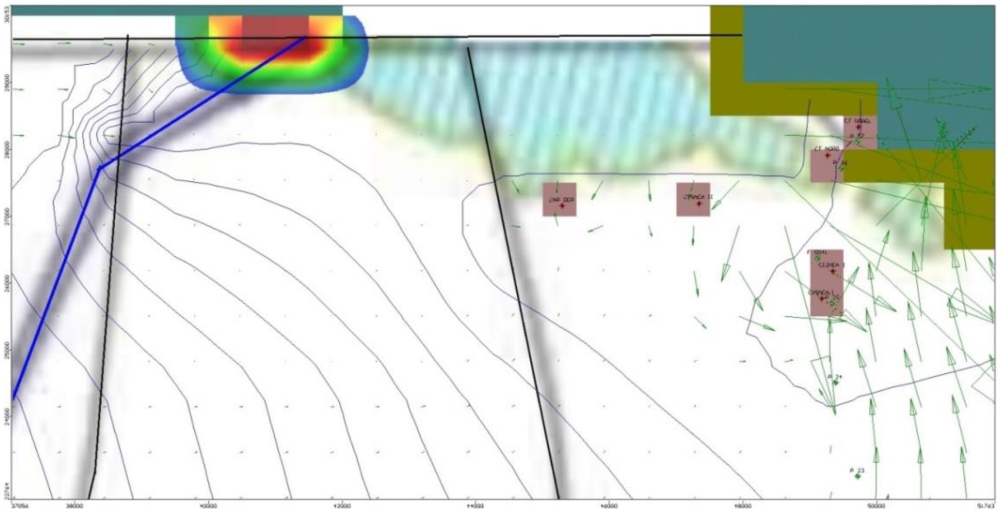


Figure 6.12. – Contaminated area after an exposure time of 30 years (calibrated model)

The simulation of the pollutant transport for the calibrated model showed that, regardless of the value of the concentration (up to the limit of 100 mg/l nitrogen) and the dispersivity, after 30 years, the effect of pollution manifests itself only in a limited area around the source of pollution. The pollutant was even introduced along the entire length of the Poarta Albă - Midia, Năvodari waterway in direct contact with the Jurassic - Cretaceous lower aquifer. Even under these conditions and for high dispersivities (of 20 m and 30 m), the simulations performed showed that, after 30 years, the effect of pollution is felt locally, on a narrow area. This is due to the hydrogeological conditions in the area (small hydraulic gradients towards catchments and Lake Siutghiol).

Later on, the same simulations were repeated, changing the exploitation flows according to hypothesis 1 (the sum of the flows captured from the sources of the Constanța municipality should be 4000 l/s).

Thus, the result of pollutant transport simulations after applying hypothesis 1 are presented at different exposure times: after 10 days, after 1 year, after 10 years and figure 6.13 – after 30 years.

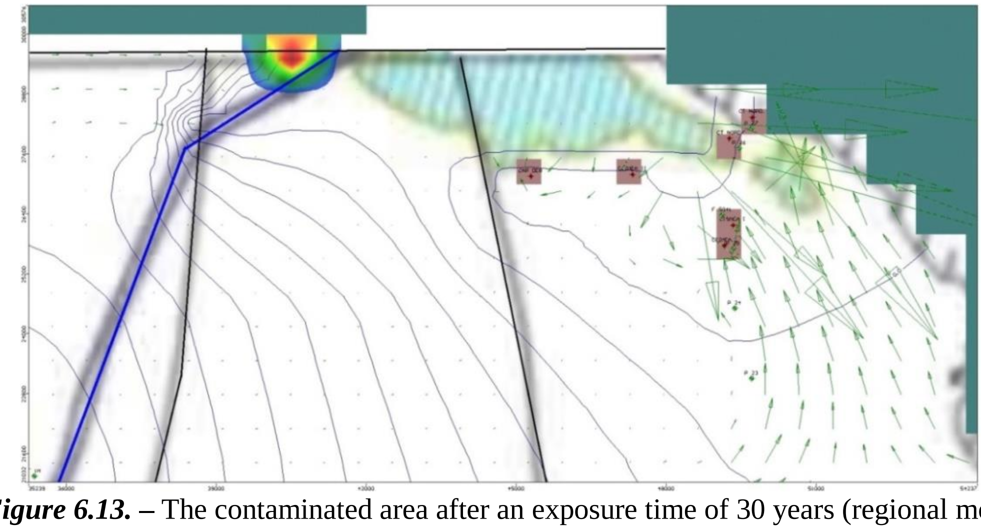


Figure 6.13. – The contaminated area after an exposure time of 30 years (regional model, hypothesis 1 of the simulation)

The transport model after increasing the exploitation flows according to hypothesis 1, showed that, regardless of the value of the concentration (up to the limit of 100 mg/l nitrogen) and the dispersivity, after 30 years, the effect of pollution manifests itself only on a restricted area of around the source of pollution. The pollutant was even introduced along the entire length of the Poarta Albă - Midia - Năvodari waterway in direct contact with the lower Jurassic - Cretaceous aquifer. Even under these conditions and for high dispersivities (of 20 m and 30 m), the simulations performed showed that, after 30 years, the effect of pollution is felt locally, on a narrow area.

The simulations carried out show that an accidental pollution in the Poarta Albă - Midia, Năvodari waterway does not extend into the lower Jurassic - Cretaceous aquifer, but is felt locally, in the area of direct contact with the aquifer. Also, the quality of the water exploited through the catchment fronts of the Constanța municipality is not altered even in the conditions of a total flow extracted from the catchment fronts increased by approximately 45% compared to the current exploitation regime.

6.5.3 Hypothesis 3 – Proposal of two new underground catchments

In order to increase operational safety and create a flexibility of the water supply system on a regional scale, the construction of two new water sources was proposed.

In tectonic block VI, good hydrogeological conditions were found from the observation drillings F 5046 – Peștera, respectively F1 – Ivrinezu Mare, in order to be able to capture water from the lower Jurassic – Cretaceous aquifer. Under these conditions, two new underground intakes with the following characteristics were simulated:

- Peștera: capture front 4 wells, drilling depth H = 500 m, catchment flow rate Q = 300 l/s;
- Ivrinezu Mare: capture front 7 wells, drilling depth H = 500 m, catchment flow rate Q = 500 l/s;

After entering the data into the regional model and carrying out simulations, the regional hydrodynamic map, presented in detail in figure 6.14, respectively the flow directions in the areas of the two catchments, presented in figure 6.15, resulted.

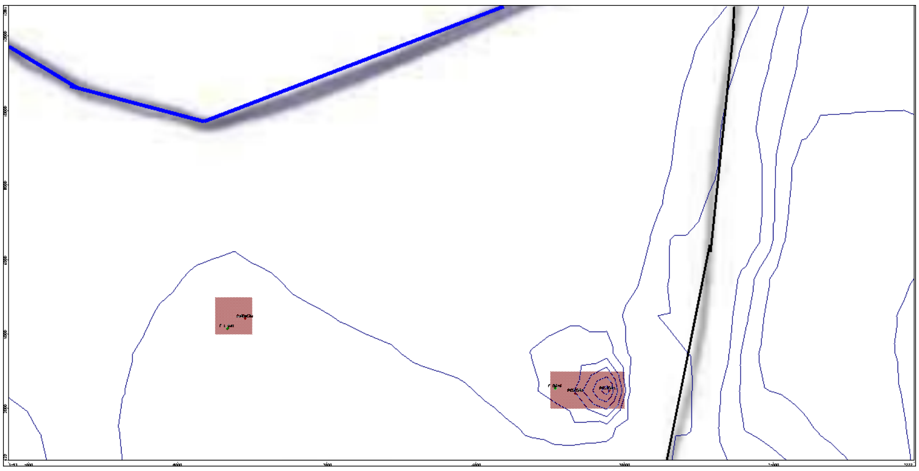


***Figure 6.14.* –** Calculated hydrodynamic map detail - proposed catchments (regional model).

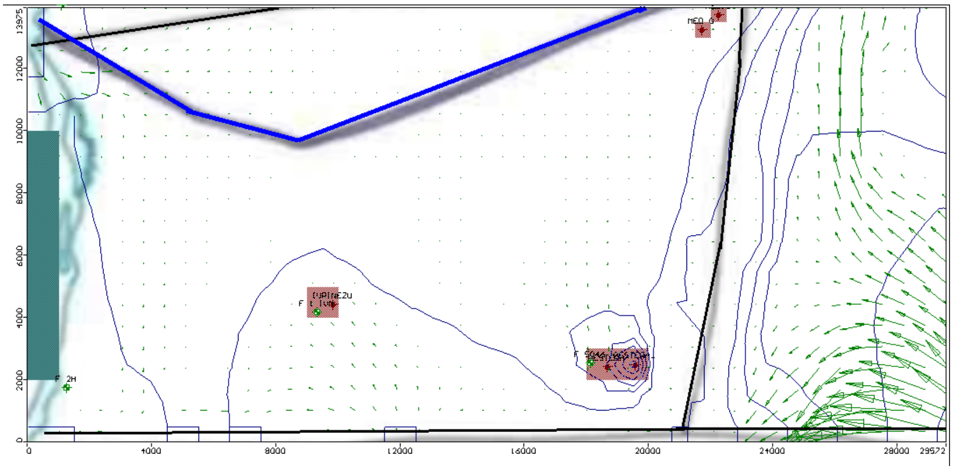


Figure 6.15. – Calculated flow directions - proposed catchments (regional model)

Following the simulations carried out, it was found that the two proposed water sources provide operational safety to the regional water supply system in the area, eliminating the risks of vulnerability to pollution in certain areas and, at the same time, providing flexibility to the system.

6.6 Local numerical model

For the purpose of more detailed research of the interaction between the Poarta Albă - Midia, Năvodari waterway and the lower Jurassic - Cretaceous aquifer, a local numerical model was also created. This model studies the region between the horizontal faults Capidava – Ovidiu and Cernavodă – Constanța, the vertical fault Nazarcea and the Black Sea.

The local model was created for an area determined by: 16 km - length, respectively 10 km - width, which was discretized in a network of cells with dimensions of 100 m x 100 m. The heights of the discretization cells are the same as in the model regionally, equal to the thickness of the lower Jurassic-Cretaceous aquifer.

The construction of the local flow model of the lower aquifer was carried out in a similar way to the construction of the regional model.

After running the local model, the hydrodynamic map of the Jurassic-Cretaceous lower aquifer, presented in figure 6.16, was obtained.

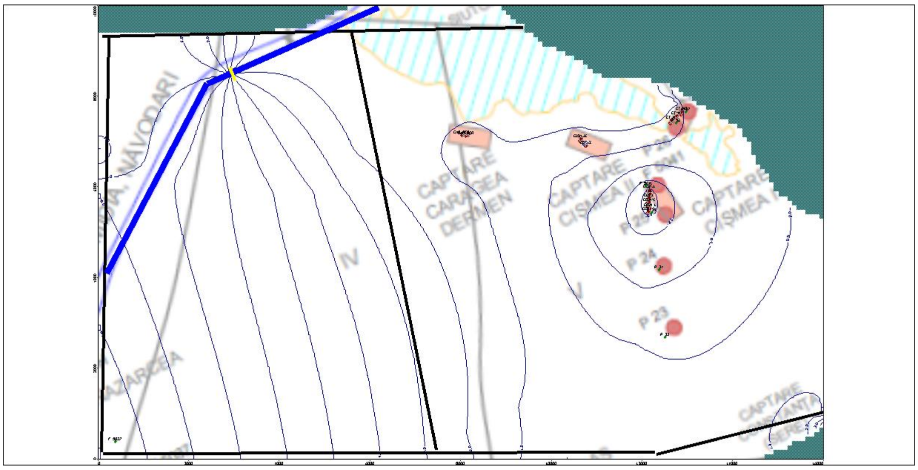


***Figure 6.16.* –** Hydrodynamic map of the local model

The flow directions resulting in the local model are oriented, as in the regional model, predominantly Southwest-Northeast, according to figure 6.17.

In the area of the Ovidiu lock, the local model shows better the local disturbance determined by the direct hydraulic connection between the waterway and the lower aquifer. It is also possible to observe in more detail the disturbances in the catchment area of the municipality of Constanța.

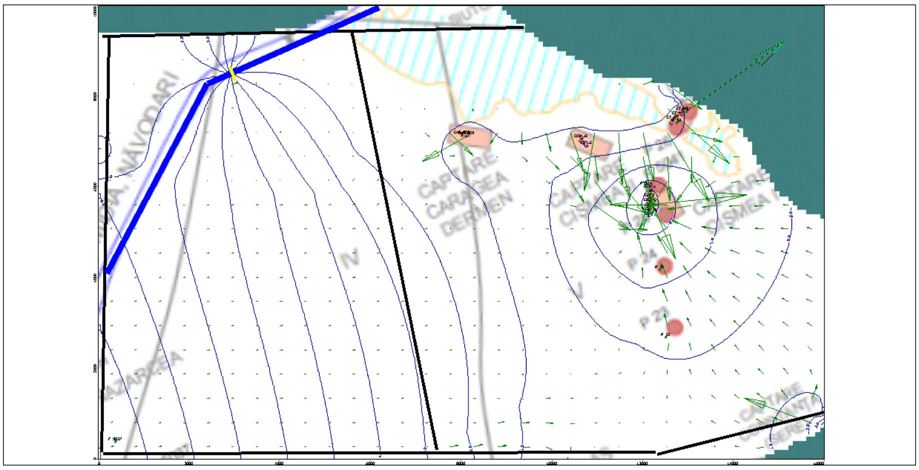


***Figure 6.17.* –** Flow directions through the local model

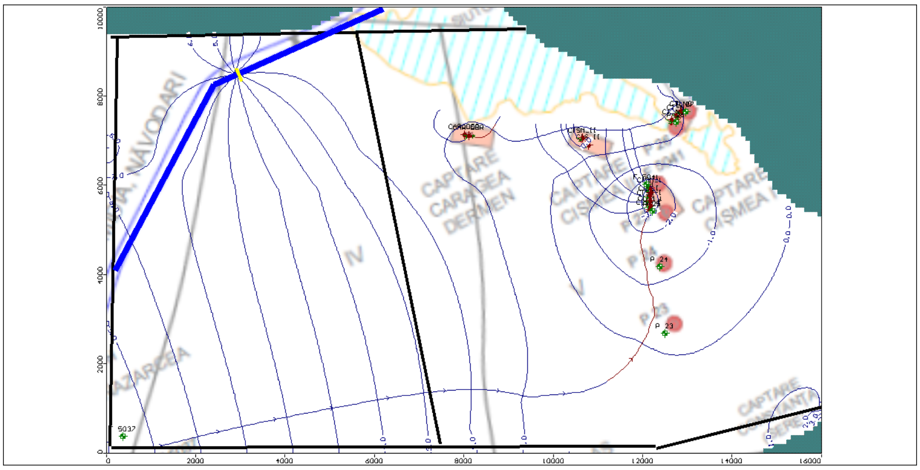


***Figure 6.18.* –** Supply areas of the catchment wells through the local model

The supply areas of local-scale catchment drillings indicate a direct connection with the water of Lake Siutghiol. Thus, it is found that in the situation of extracting large flows that exceed the optimal exploitation regime, drops in the water level in the lake may occur.

The local model was also used for the simulation of two hypotheses: the increase of the flows exploited from the Constanța catchments up to 4000 l/s, respectively the transport of pollutants from the area upstream of the Ovidiu lock.

6.6.1 Hypothesis 1 – The increase of debits

After applying hypothesis 1 and running the local model, it resulted the hydrodynamic map of the lower Jurassic-Cretaceous aquifer, presented in figure 6.19.

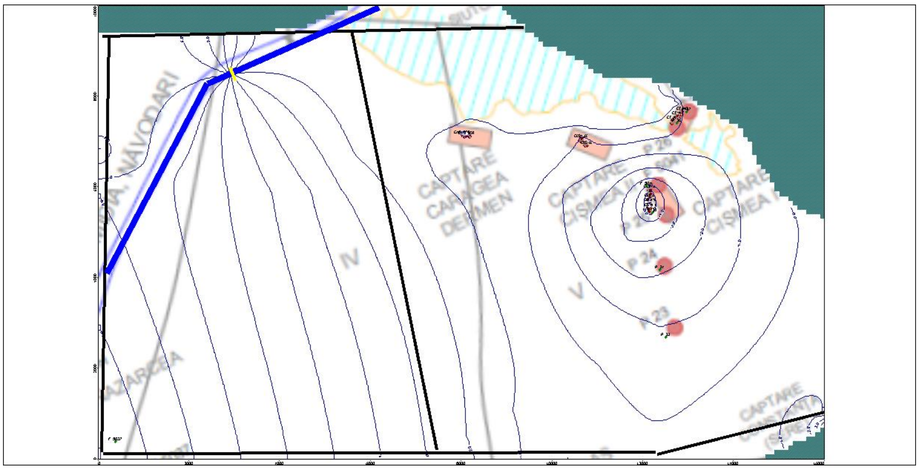


Figure 6.19. – Calculated hydrodynamic map (local model, simulation hypothesis 1)

The resulting flow directions in the local model simulated with hypothesis 1 are also predominantly oriented South-West – North-East.

The supply areas of local-scale catchment model after applying hypothesis 1 indicate the same direct connection with the water of Lake Siutghiol.

6.6.2 Hypothesis 2 – Pollutant transport

The local numerical model made was further used for the simulation of pollutant transport, also taking dispersion into account. At the same time, the same simulations were carried out as in the regional model, for several scenarios of accidental pollution. A pollutant was also introduced into the area of the Ovidiu lock, from the Poarta Albă - Midia waterway, Năvodari, on the section in direct hydraulic contact with the lower aquifer. The simulations were made for a maximum period of 30 years, considering the quasi-stationary flow regime, while the exploitation flows from the underground catchments had both a variant with the values provided by the operator RAJA Constanța, and another variant with the values calculated for a total flow exploited from the sources of the Municipality of Constanța (according to hypothesis 1) of 4000 l/s. The investigated pollutant had a concentration of 100 mg/l, while the dispersivity of the medium was varied. The results of pollutant transport simulations for the local model using the operating flows provided by RAJA Constanța operator are presented at different exposure times - after 1 year, after 10 years and figure 6.20 - after 30 years.

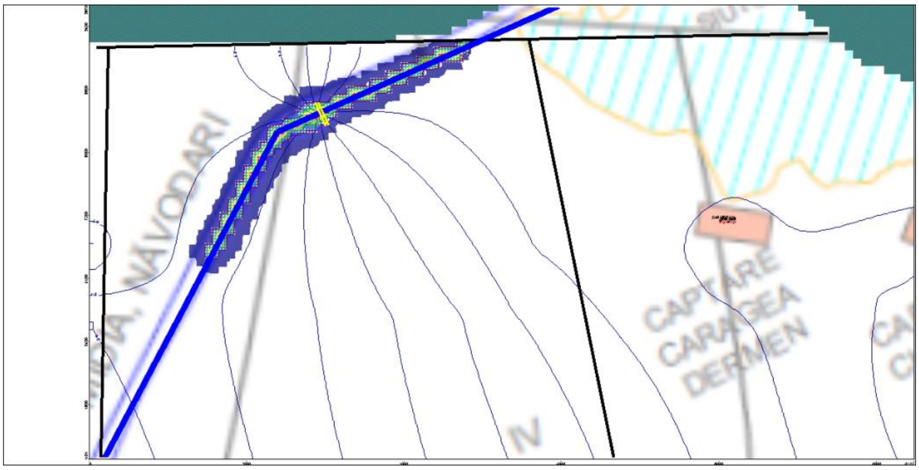


Figure 6.20. – Contaminated area after an exposure time of 30 years (local model)

After the pollutant transport simulations carried out for the local model, it is observed that regardless of the value of the concentration (up to the limit of 100 mg/l nitrogen) and the dispersivity, after a period of 30 years, the effect of pollution manifests itself on a relatively small area of around the source of pollution.

Later, the same simulations were repeated, changing the exploitation flows according to hypothesis 1 (the sum of the flows captured from the sources of the Constanța municipality should be 4000 l/s).

Thus, the results of pollutant transport simulations after applying hypothesis 1 are presented at the same exposure times.

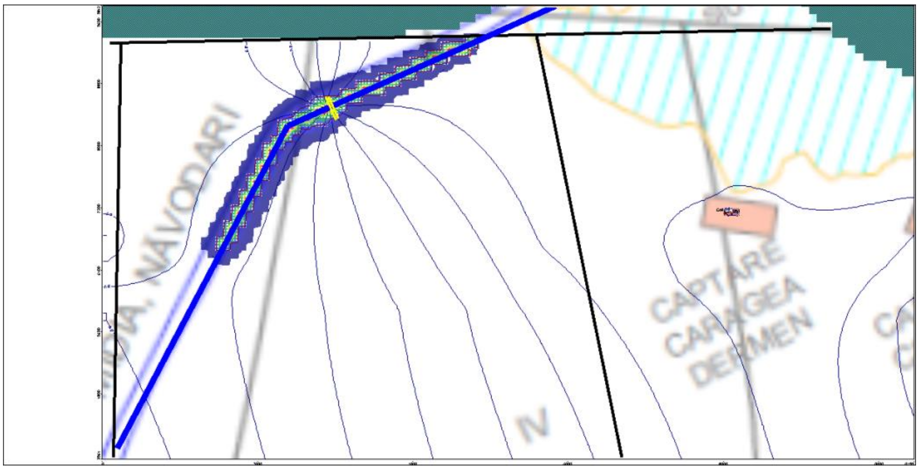


Figure 6.21. – Contaminated area after an exposure time of 30 years (local model, simulation hypothesis 1)

And after increasing the exploitation flows according to hypothesis 1 in the local model, it was found that at values of concentration up to the limit of 100 mg/l nitrogen and of various dispersivities, after 30 years, the effect of pollution manifests itself only on a relatively small area of around the source of pollution. The pollutant was even introduced along the entire length of the Poarta Albă - Midia - Năvodari waterway in direct contact with the lower Jurassic - Cretaceous aquifer. Even under these conditions and for high dispersivities (of 20 m and 30 m), the simulations performed showed that, after 30 years, the effect of pollution is felt locally, on a narrow area. This is due to the hydrogeological conditions in the area (small hydraulic gradients towards catchments and Siutghiol lake) and especially to the water drainage in the downstream section of the Ovidiu lock, where the imposed load is + 1.25 m.

The simulations carried out in the local model highlight the idea also derived from the regional model, that an accidental pollution in the Poarta Albă - Midia, Năvodari waterway does not extend into the lower Jurassic - Cretaceous aquifer, but is felt locally, in the area of direct contact with the aquifer. Also, the quality of the water exploited through the catchment fronts of the municipality of Constanța is not significantly altered even in the conditions of a total flow captured from the catchment fronts increased by approximately 45% compared to the current exploitation regime.

7 PROPOSED MEASURES TO REDUCE RISKS

Following the presented research activity, a series of recommended measures are proposed to reduce the risks from water supply activities for the population.

7.1. Measures regarding the design of water sources

Exploitation of underground water sources located in the vicinity of waterways can generate risks of changing the flow regime in the intercepted aquifer layers (fissural - karst), as well as risks of changing the quality of the underground water stored in them, if a series of measures are not adopted of protection customized for each location..

In the area researched in this paper, there are exploited underground water catchments that ensure the water supply of the coastal towns. Being a tourist area, the main peculiarity in operation is that in the summer season the demands for drinking water increase spectacularly, and in some situations the water sources are forced to exploit very high flows, above the calculated values. In the researched area, the studies carried out by various authors indicated a value of the hydrodynamic resource of the Jurassic - Lower Cretaceous aquifer of the order of 8.0 m^3/s. [50].

In order to design and implement new sources of drinking underground water, it is necessary to carry out hydrogeological, geophysical, hydrodynamic, topographical studies, etc. according to the presented logic schemes..

MEASURES FOR THE DEVELOPMENT OF STUDIES AND PROJECTS FOR THE PROPOSED SOURCES

- ***STUDY PHASE***

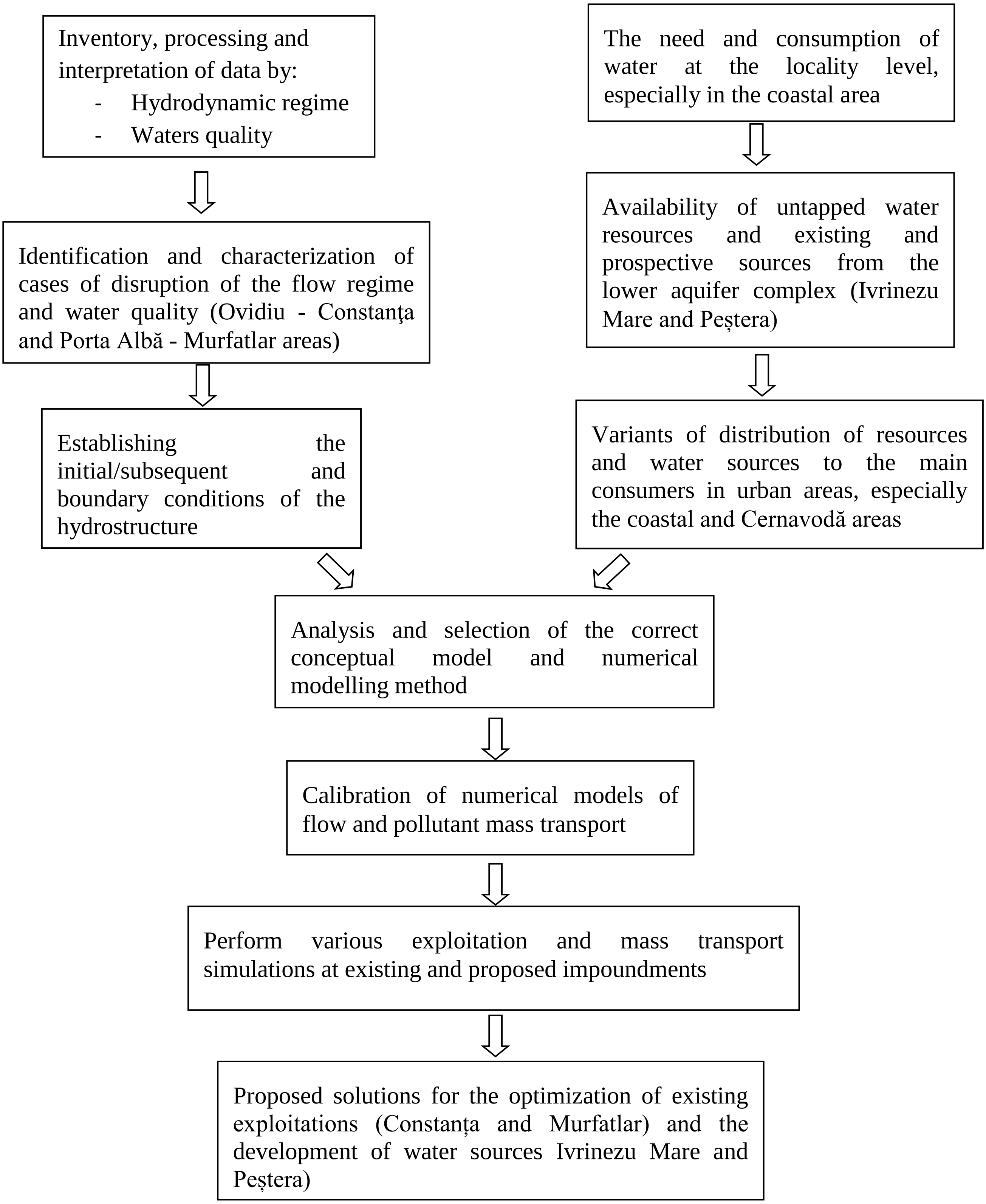


Figure 7.1. – Logical scheme proposed measures for studies

➢ ***TECHNOLOGICAL DESIGN PHASE***

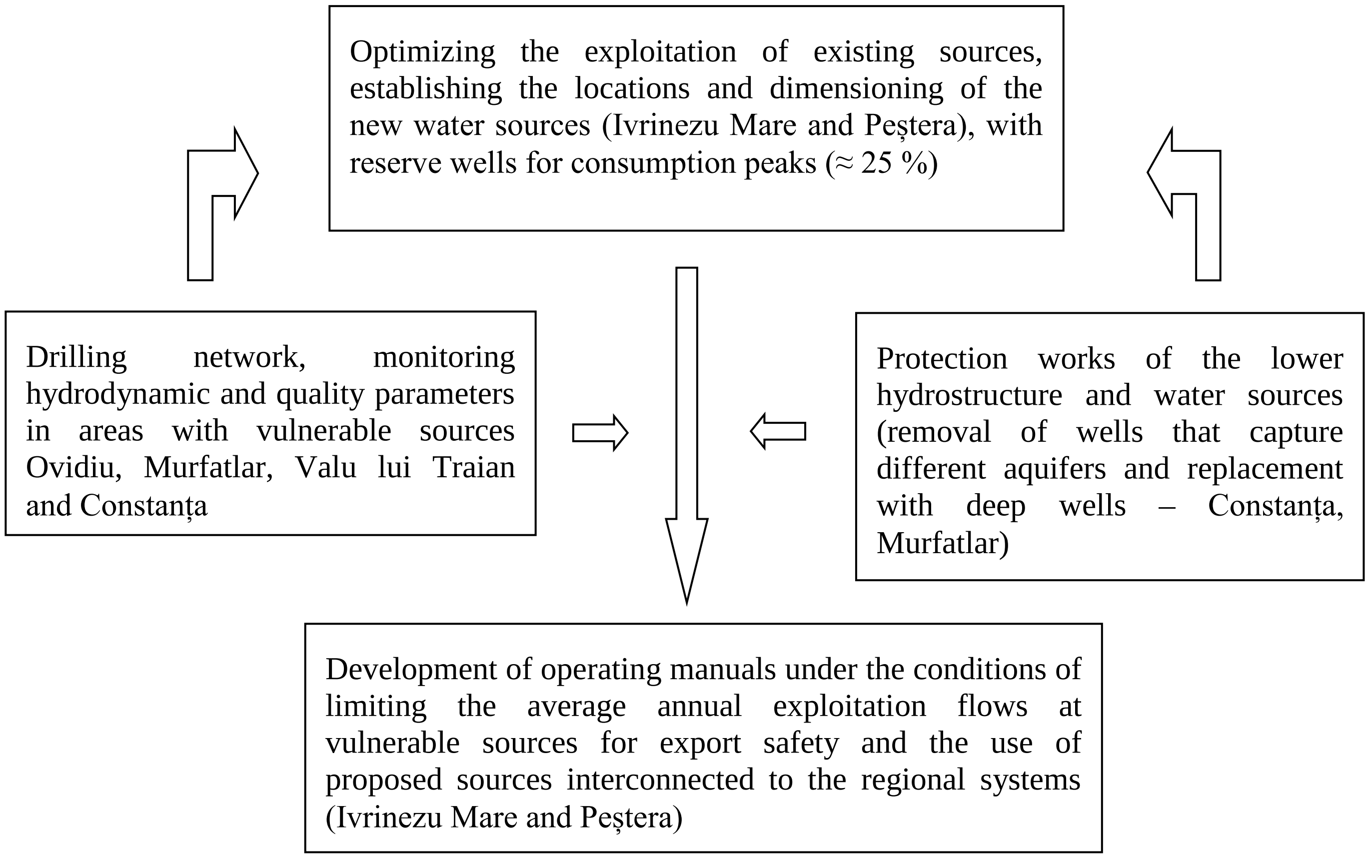


***Figure 7.2.* –** Logical scheme proposed measures for design

7.2. Measures for operational safety

The area researched in this paper is known as an arid area with a reduced hydrographic network.

Justifiably, in the researched area regional supply systems were used, interconnected, provided with many sources of underground water of good quality and stable over time. Following the execution and exploitation of large-scale investments (irrigation systems, waterways, underground water catchments) in recent years, important changes have been registered in the flow regime and quality of underground and surface waters.

The impact of human activities manifests itself unfavorably both on exploitable water resources and the ecological balance in the area, as well as on the operational safety of water supply systems for the population.

The synthetic presentation of preventive measures for operational safety of the water supply system in the researched area is described in the table below:

PREVENTIVE MEASURES FOR SAFETY IN OPERATION

CAUSE	PREVENTIVE MEASURES	INSPECTION	REMEDIAL ACTIVITIES
1. CONTAMINATION OF THE LOWER AQUIFER			
infiltrates from the waterway (Murfatlar, Ovidiu) infiltrations from other aquifers through vertical drainage (Murfatlar) infiltrations from chemical sources in the aquifer supply area (Poarta Albă, Ovidiu)	* identification of pollution sources * reducing or stopping the operation of the source * use of backup sources * documentation regarding the aquifer supply conditions	* the content of pollutants * operating parameters * water quality parameters	* monitoring program, in the Constanța catchments to obtain data * elimination of pollution sources from waterway discharges * updating preventive measures with the situation encountered * investment design additional protection and deep wells to existing water sources
2. THE SOURCE DOES NOT PROVIDE THE DESIGNED QUANTITY OF WATER			
overexploitation of water sources located in the vicinity of Lake Siutghiol (Constanța) and waterways (Ovidiu and Murfatlar) damaged or blocked filter column (where present) submersible pump failure	* identification of areas with disturbance of the underground water flow regime * inspection and cleaning of the filter columns of the wells * periodic inspection program of filter columns * the use of backup sources	* capture rate * flow of each well and hydrodynamic levels * comparison with the initial flow - elevation diagrams	* modification of the exploitation regime of the catchments in order to limit the exploitation flows * rehabilitation of problem drillings * changing the capture in the sense of increasing the depth of the drillings * replacement of defective pumps * pump maintenance schedule on a regular basis
3. SUPPLY SYSTEM DOES NOT HAVE SUFFICIENT WATER AT VF. FOR CONSUMPTION			
large seasonal consumption variations specific to the area malfunctions / breakdowns in the operation of water sources accidental contamination of water sources	* designing well-protected backup sources * interconnection with other zonal systems * development of existing sources through deep drilling	* water requirements * rate of use of existing sources * analysis of water losses through distribution * available water resources in naturally protected areas	* the execution of two water sources in protected areas: - Ivrinezu Mare - The cave * the execution of links for the interconnection of systems (in the coastal area) * connecting the new sources to the zonal systems

Table 7.1. – Preventive measures for operational safety

8 CONCLUSIONS

According to regional / local scale research, the following observations can be made:

- **Distortions of the hydrodynamic spectrum** at the scale of the researched area => reflect the effect of water catchment exploitation and local influences determined by waterways;
- **The flow directions have not undergone substantial changes** compared to the situation before the construction of the waterways;
- **The variation of hydraulic gradients** when groundwater flows is between 0.0002 and 0.0016;
- **Flows infiltrated from the tributary upstream of the Ovidiu lock with an elevation** of +7.5 m into the lower aquifer **=> drained by the tributary downstream of the lock**, with an elevation of +1.25;
- **A small percentage of the infiltrated flows from the tributary upstream of the Ovidiu lock => can be drained by exploiting the Caragea - Dermen catchment,** but by dilution with water from the lower aquifer, it does not currently constitute a risk of contamination**;**
- In order to maintain the operational safety of the underground water intakes of the municipality of **Constanţa** => it is recommended to limit the average annual flow rate exploited to Q med = 2500 l/s;
- In order to maintain the operational safety of the underground water intakes of the **Murfatlar** town => it is recommended to limit the average annual flow rate exploited to Q med = 600 l/s => it prevents the formation of the downward vertical drainage process;

- For the underground **water source Medgidia => no influence of the waters from the Danube - Black Sea waterway** is found, due to the construction of the wells (perfect isolation by cementing the definitive columns of the phreatic aquifers - interval 0.00 - 150.00 m).
- A series of applied simulations are presented in the paper::

- **hypothesis 1:** *the increase in average annual flows from the Constanța catchments*,

- **hypothesis 2:** *contamination of the lower aquifer in the case of water pollution from the Poarta Albă – Midia, Năvodari waterway on the upstream section of the Ovidiu lock*

- **hypothesis 3:** *hydrodynamic influence of two new proposed groundwater catchments*

$\Rightarrow$ to maintain safety in the exploitation of water sources and implicitly of waterways.

- **The pollutant transport simulations** were carried out both for normal exploitation flows and after the application of hypothesis 1 => **a local effect is felt**, even after an exposure time of 30 years..

- To increase operational safety and create a flexibility of the water supply system on a regional scale => it was proposed to build two new water sources located at **Peștera (Q=300 l/s) and Ivrinezu Mare (Q=500 l/ s);**

8.1. Personal contributions and elements of originality

The author has included in this work a series of **personal contributions**, both in the study stage in the researched location, and in the methodology of processing the obtained data:

- clarification of the geological structure and flow conditions in the fissural karst aquifer complex from the location of the waterways;
- the selection of a network of drillings, from the existing ones, and the measurement of piezometric levels for the construction of the hydrodynamic spectrum on a regional scale;
- reinterpretation of data from experimental pumping in selected drillings, taking into account the imperfection according to the degree of opening of the aquifer and calculation of the main hydrogeological parameters;
- preparation of the updated piezometric map for the karst fissure aquifer complex (lower), after 35 years of exploitation of the waterways;
- creating a conceptual flow model, based on a set of simplifying assumptions, in order to substantiate a numerical model;
- building a numerical model of water flow and mass transport to simulate the evolution in different situations;
- proposing some necessary measures in the design of waterways to ensure the protection of underground water resources;
- proposing specific recommendations for the location and design of groundwater intakes in the vicinity of waterways;
- making recommendations for the exploitation of existing water sources in vulnerable areas;
- making recommendations for the design and execution of monitoring drilling networks in the main vulnerable areas.

The results of the PhD thesis were capitalized by the publication of several scientific articles, presented below:

- Moldoveanu, M.; Bica, I. - Interaction of waterways located in karst fissure areas and groundwater, Universitatea de Stiinte Agronomice si Medicina Veterinara Bucuresti, Conferita internationala Agriculture for life, life for agriculture, Iunie 2020, Bucuresti.

- Ciocan, V.; Moldoveanu, M. - Analysis of the behavior of the works to limit the water erosion in the river basins, Universitatea de Stiinte Agronomice si Medicina Veterinara Bucuresti, Conferita internationala Agriculture for life, life for agriculture, Iunie 2020, Bucuresti.

- Moldoveanu, M. - Masuri de crestere a sigurantei in exploatare a surselor de apa subterana situate in vecinatatea canalelor navigabile din judetul Constanta, Universitatea Tehnica de Constructii Bucuresti, Revista Buletinul Stiintific al Universitatii Tehnice de Constructii Bucuresti, 2020, pag. 32 - 40.
- Moldoveanu, M.; Moldoveanu, V. - Asigurarea alimentarii cu apa a zonei litorale romanesti din resurse carstice protejate natural, Asociatia Parteneriat Pentru Proiecte si Fonduri Europene, Revista Edilitatea, nr. 8 - Martie 2022, pag. 14 - 22.

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