Hydrogeological Review of the Raša Coal Mine in the Coastal Karst of Croatia

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ABSTRACT

The coal mine of Raša is situated in the Istria peninsula within the coastal karst of Croatia (Fig 1). Black coal with a high calorific value was mined there but the production was rather small. The coal lies at the bottom of thick Tertiary flysch and limestones, directly above Upper Cretaceous limestones within a fan-like synclinorium dipping northward.

In 1934, a long mine gallery struck a water-bearing zone (cavern) at the depth of 140 m below sea level through which saline groundwater penetrated at a high rate of flow. This occurred about 3.5 km inland from the nearest Adriatic Sea coast. The inflow was stopped with sand bags and a concrete plug provided with a valve and manometer. Further coal excavation was stopped leaving about 866,000 tons of coal, or, some 20 years of possible mining, blocked by the plugged cavern.

In 1954, Prof.J.Baturić and his students carried out some complex tests on the discharges of water from the plugged cavern with observations of flow rates, pressure and salinity of water. These tests provided valuable data on water salinity changes with respect to the different rates and duration of discharge and on the maximum rates of prolonged flow, 13.5 m^3/min, when water salinity reached that of an almost pure sea water, 32.6 g/l NaCl. A thorough study of the obtained data, including an interesting analysis of several possible groundwater flow patterns, gave the basis to an argumented estimate of the maximal possible rate of discharge and suggestions on how to decrease that rate. This mine represents a valuable and unique case for the understanding of coastal karst hydrogeology, particularly its geohydraulics.

This paper is an homage to a mining engineer, the late J.Baturić, who brilliantly conducted and interpreted the discussed exploration.

INTRODUCTION

The Raša coal mine is situated in an area belonging to the region known as *locus typicus* of karst terrains only several tens of kilometres far from the area from where the word *karst* derives (Fig 1). A countless number of kilometres of mine galleries and other passages were excavated over a period of more than 200 years of permanent mining.

Since coal deposits are over- and underlain by limestones deformed and considerably permeable at the zones of long faults, it is no wonder that groundwater breakthroughs took place during the mining. One of them occurred deep below the sea level and rather close to the sea coast causing a large penetration of saline groundwater. Since 1934, when that breakthrough happened, mining was stopped in the affected part of the mine, mine field 5, leaving about 870,000 tons of high-calorific black coal confined by ground- and sea water.

Twenty years later, Prof. J.Baturić of the University of Zagreb with a group of his mature students carried a complex exploration including several short and one prolonged test on the discharges from the breakthrough site named the *Kaverna*. The exploration methods, data and interpretation are a valuable, perhaps even exceptional, contribution to the coastal karst geohydraulics. The following chapters deal with that work and with a brief review of the mining activity and hydrogeological setting of the Raša mine area.

There are also certain sentimental reasons. The author of this paper (A.Š.) was a member of the group of students which, lead by J. Baturić, carried out the discussed exploration. That work was to be his graduation thesis subject. He also cannot forget an extremely tense and fearful atmosphere that existed when the professor, a young mining engineer, a worker and he were present during the first opening of the valve in the concrete plug for the test discharges, when groundwater began to flow out turbulently under a pressure of 14 atm creating the noise of a train going through a tunnel.

MINING ACTIVITY

Mining in the Raša coal mine area started in the 18th century and has ceaselessly continued since that time. The coal occurs in the form of fan-like deposits at the edge of the Labin-Pićan basin, within the southern part of the Istrian synclinorium. Along that edge, the Istrian Coal Mines consisting of seven mines, one of them being the Raša mine, have been developed but the mining ended in one of them a long time ago and exploitation started recently in one of others.

Black coal with a high calorific value, near 27.000 KJ, is mined there. Meanwhile, the production is small, approximately 270,000 tons annually from the Raša mine during the last few years. In total, some 30 million tons of coal have been extracted from that mine.

Three of the mines, one of which is the Raša mine, have mutually connected mining areas and galleries and extend about 6.5 km along the strike while not more than 1 km down along the dip.

The deepest galleries of the Istrian mines reach a depth of about 800 m below the land surface and about 500 m below sea level, while these figures are 200-250 m and 180 m, respectively, at the Raša mine.

Fig.1 Situation of the "Kaverna" groundwater breakthrough in Raša coal mine

All these mines make a huge drainage area. The one of the Raša mine surpasses 10 km^2. Owing to the fact that the precipitation is rather abundant and the limestones very permeable, large amounts of water were permanently pumped from the mines. In 1985, an average of about 57 m^3/min of water was pumped from all the active mines. About 18 m^3/min was pumped from the Raša mine in 1984.

In 1934, a long gallery of the Raša mine struck a water-bearing zone in limestones from which fresh groundwater with mud began to flow out under high pressure and a great rate of discharge(1). The water was fresh in the beginning but it soon became saline. This occurred at a depth of 140 m below sea level and about 3.5 km from the nearest point of the Adriatic Sea coast. The inflow was stopped by means of sand bags only after several attempts leaving some 600 m of the mine gallery totally drowned. The fifth barrier was finally effective and it was secured by a so-called water door. In 1949, the door was replaced by a concrete plug provided by a valve with a manometer.

Mining was stopped in that part of the Raša mine, that is mine field 5. That mine field comprised about 870,000 tons of coal that could have been excavated during the next about 20 years. The mine area, comprising the cavern from where the groundwater penetrated and the concrete plug site, is called the *Kaverna.*

In order to solve the problem of the Kaverna breakthrough, J. Baturić of the University of Zagreb carried out a complex hydrogeological exploration in 1954[1].

The mine's itself performed certain hydrogeological observations during 1954 and 1958 within which several tests on the discharges from the Kaverna took place as well[2].

In 1959, the Geotehnika company of Zagreb performed underground grouting in the zone of Kaverna[3]. It was aimed to fill the caverns and wide fissures around the breakthrough site in order to avoid turbulent velocities of groundwater which appear at the discharges under high pressure. That is to say, Baturić warned that such turbulent velocities of water might move the deposited mud in the caverns and fissures making the rock more permeable, and that would cause greater rates of groundwater flow out from the Kaverna.

However, coal mining has not ever continued in the mine field 5, i.e. in the zone of Kaverna. The swan song of Istrian coal mining happened in 1976 when, subsidized by the regional electric power authority, a comprehensive exploration and new mine constructions vere made. However, in 1987, it was decided to stop any further investment in the development of the Raša mine because of a complex macro- and microtectonics and small quantifies of the deposits, environmental concern (high sulphur content) and danger of sea water intrusion. Thus, the mine was gradually closed between 1987 and 1989. The flooding of the mine started in 1988 and ended in May 1991 when water began to flow out freely from the mine gallery into the sea.

HYDROGEOLOGICAL SETTING

The mine is situated in the eastern coast of the Istrian Peninsula, some mine sections being only two kilometres distant from the Adriatic Sea.

The oldest rocks opened by the mine are massive to thick-bedded Upper Cretaceous limestones[2]. After a long emergence, the whole region was transgressively overlain by Paleocene to Lower Eocene freshwater coal deposits (Kozina formation). Over them, Middle Eocene marine foraminiferal limestones were concordantly deposited. The series ends upward with thick Eocene deep-marine flysch deposits consisting of marls, marly limestones and sandstones alternately.

Post-Eocene folding, thrusting and faulting formed the present coal deposit. The discussed mine field 5 is the upper part of a syncline. The syncline gradually broadens and dips northward reaching the depth of 550 m below sea level at the distance of about 7 km.

The annual precipitation on the studied mine area range around 1000 mm and about half of it is infiltrated through the limestones into the underground. Most of that water has been pumped out from the mine. The pumped water contained not only the water deriving from the precipitation but also from sea water penetrations taking into account that the field 5 is about 140 m below sea level, 3.5 km far from the coast and the rocks are permeable Upper Cretaceous limestones. Sea water has a good hydraulic contact with the fresh groundwater of field 5 in some places and with the mine itself through caverns and fissures developed particularly along fault zones.

COMPLEX EXPLORATION OF 1954

Josip Baturić, late professor of applied geophysics and mining surveying of the University of Zagreb, having been very active in groundwater exploration in Croatia in the 50-ties, got approval from the managers of the Raša mine to carry out a complex hydrogeological exploration. He did it with a group of his mature students in 1954.

The exploration was focused (1) on several short and one prolonged discharges of groundwater by the opening and the closing of the valve in the concrete plug of the Kaverna and (2) on continuous measurements of discharge rate, water salinity and ground water pressure behind the valve and near the groundwater breakthrough (in two mine boreholes)(1). It was accompanied by geoelectric exploration (resistivity sounding and profiling) in the parallel footwall gallery in Cretaceous rocks performed at the beginning in the middle and at the end of the test discharge.

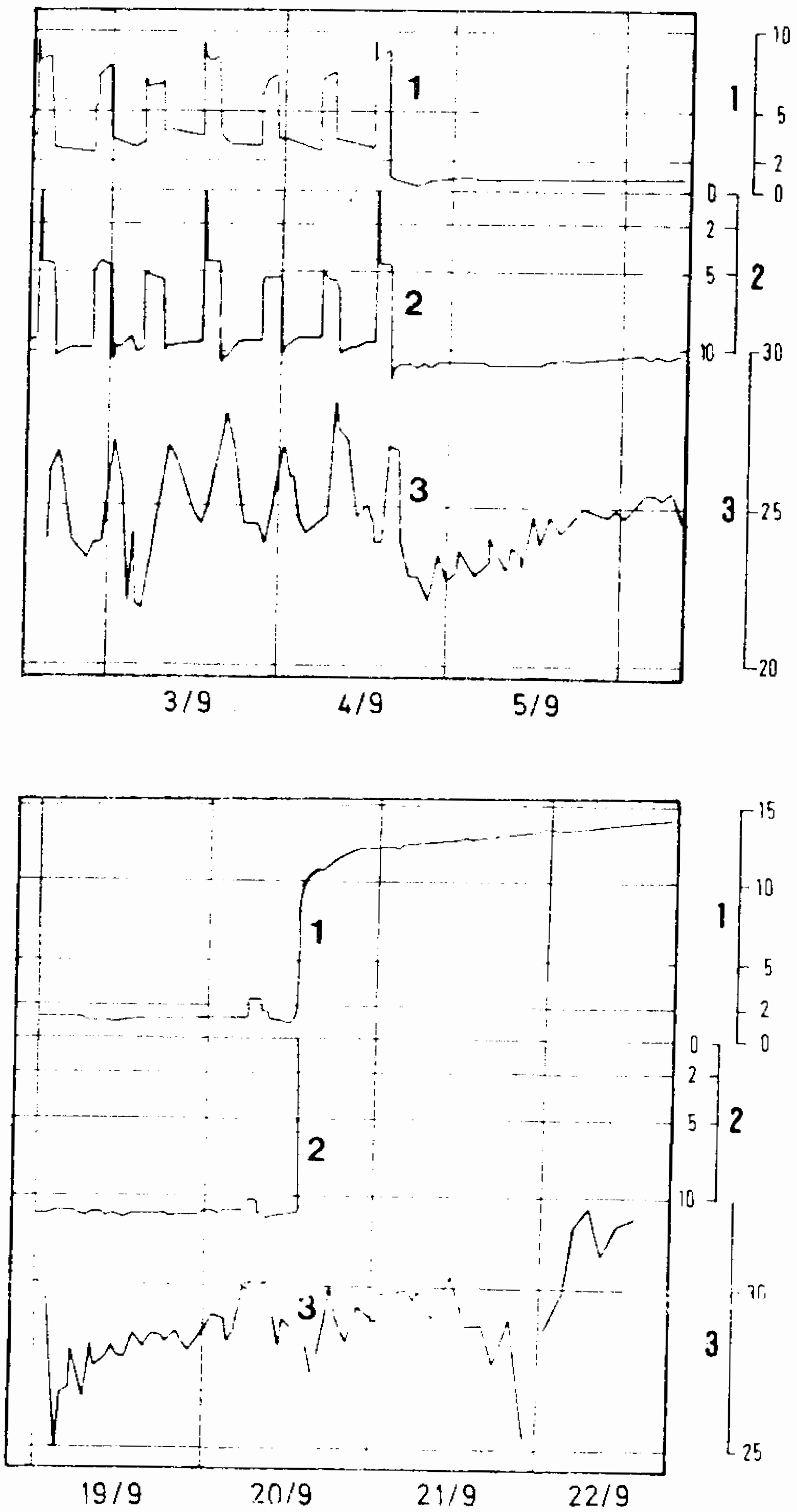

Fig.2 A part of short- and longlasting test discharges of September 1954 (after Baturić)
1 - water pressure (atm), 2 - rate of flow (m^3/s), 3 - water salinity (g/l NaCl)

The first discharge started on 27/8/1954. The valve was opened and closed several times till September 4th when it was entirely opened and left so till September 20th when it was finally closed.

Furthermore, precipitation records from 1/10/1953 to 30/9/1954 in the three nearby observation stations and all the records of mine dewatering during that hydrological year were collected and studied. Water salinity from the Kaverna and seven more sites in the mine were observed during that whole year.

EXPLORATION DATA AND THEIR INTERPRETATION

The three rain gauge stations, the data of which were used in the study, showed the annual precipitation ranging between 919 mm and 1174 mm during 1953/54 or average of 1023 mm[(1)].

The recharge area comprises about 10.3 km^2 and some 50% of that was supposed to be infiltrated into the underground. So, about 10.0 m^3/min of average precipitation reached the field during the hydrological year 1953/54. That figure corresponded ideally with 9.6 m^3/min, i.e. the average amount of water pumped out from the mine during that period.

Maximal rate of test discharge from the Kaverna was 11.6 m^3/min and numerous graph-analytic calculations showed that it may rise to a maximum of up to 13.5 m^3/min at the concrete plug and not more than 16 m^3/min 600 m further in the immersed gallery at the site of real groundwater breakthrough.

Water pressure rose abruptly to 9 atm after the final closing of the valve, after a 16-day continuous flowing out, while it took much more time to approach its initial 14 atm (Fig.2). That difference could not be explained by a normal behaviour of the water pressure during the recovery stage, after the pumping from the well situated in a homogeneous porous medium. Baturić explained it by the very nature of the rocks at the Kaverna, by their heterogeneous porosity, i.e. by their fissures and caverns. That is to say, he supposed that there were no large openings in the rocks within the lower 90 m above the Kaverna. He found support for that assumption in the detailed geological data of that area as well as in the resistivity sounding performed from the mine itself.

The first available water salinity, that one from a sample taken on August 27th, showed 17.6 ~~m~~g/l of NaCl. The NaCl content gradually rose to about 27 mg/l during the short and intermittent test discharges fluctuating in dependence of whether the water was flowing out or not. During the last, 16-day continuous flowing out, 4-20 Sep. 1954, the salinity ranged between 27 and 30 mg/l. Two days after the end of continuous discharging, the water salinity at the Kaverna was that of a pure sea, 32.6 g/l NaCl (Fig. 2.). The fluctuation of salinity, its rise and final sea-water salinity were explained (1) by the characteristics of an elastic karst aquifer, (2) by the existence of the 600 m long mine gallery beyond the concrete plug and (3) by an ever bigger share of penetrated sea water during the long-lasting test discharges.

It was supposed that the sea water penetrated into the cavern from a small bay of Koromačna about 11 km to the south of the mine. Much closer, the bay of Duga Luka only 3.5 km away was rejected as a site from where sea water could penetrate. Anyway, the exact position of the sea water entrance (or entrances) is not important in this case taking into account that a coastal karst aquifer is concerned and that the groundwater breakthrough occurred 140 m below sea level.

A series of graphical analyses and hydraulic computations convinced Baturić that the underground flow was of a laminar type and that a zone of narrow fissures existed between the sea and the Kaverna (Fig. 3 and 4).

CONCLUSIVE CONSIDERATION

This chapter deals, basically, with the reasons which motivated the authors to write this paper. In doing that, certain conclusive considerations will emerge as well.

The paper has not been written to describe either a mine dewatering case study, or a case study related to the coastal karst hydrogeology. Nor the reason for writing was to review J. Baturić's work - either the performed exploration or the interpretation of exploration data.

One of the reasons lies in the desire to draw the scientific community's attention to an interesting problem involving mine dewatering and karst hydrogeology, or more specifically, a complex coastal karst hydrogeology. That is to say, it is necessary to take into account that the discussed groundwater breakthrough occurred 140 m below sea level and only 3.5 km far from the Adriatic Sea coast while the surrounding rocks are karstified limestones. The area is known for its countless underground karst forms described in the book *Two thousand caves* [4]. That area is adjacent to the heart of the region known as *locus typicus* of global karstic terrains[5]. Furthermore, that coast (together with the whole northwestern half of the Adriatic Sea) gradually submerged during the last about 25,000 years[6]. It had earlier been some 100 m above the present position if compared with the sea level. Thus, the entire region underwent long (between the deposition of Eocene flysch and those about 25,000 years ago) and intensive karstification processes.

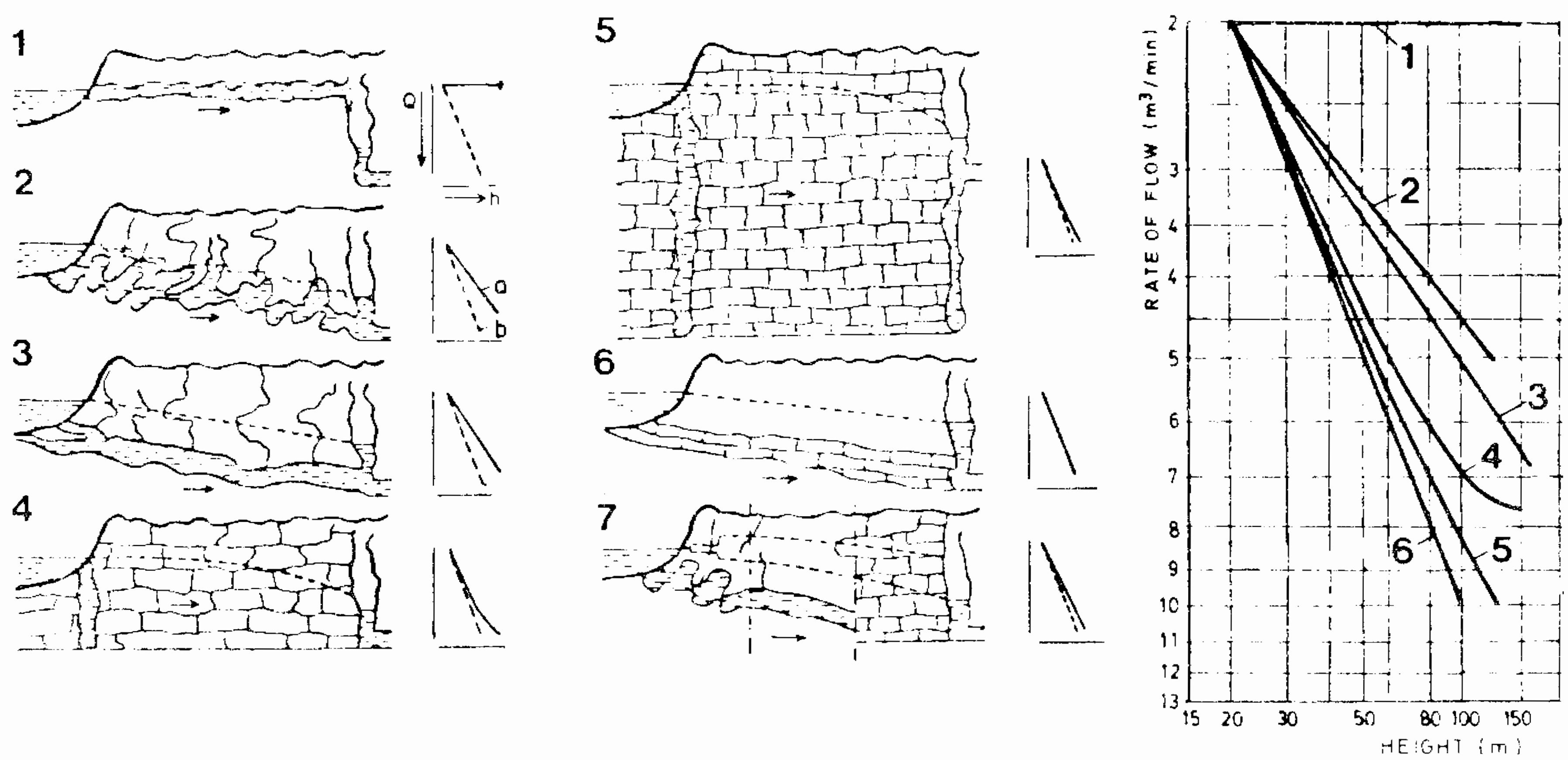

Fig 3. Possible types of groundwater flow (after Baturić)
1 - waterfall, 2 - local losses, 3 - turbulent flow, 4 - filtration I, 5 - filtration II, 6 - laminar flow, 7 - combined types of flow, a - individual type of flow, b - laminar flow

The discussed exploration, performed by Prof. Baturić and his students in 1954, abound in various geohydraulic data processed in different graphical and analytic ways using several hydraulic and laboratory solutions. The procedure and interpretation were fully explained and prooved in a comprehensive paper[1]. In that paper, 36 diagrams, graphics and situation sketches were used to show the various possible underground flow patterns, as: "waterfall", local losses, various filtration, turbulent and laminary flows. All the test discharge data were presented, in the diagrams under their various interdependence showing the rates of flow, water pressure, various possible and most probable sizes (diameters) of underground conduits, underground flow velocity and various hydraulic terms (as h/Q^2, $(h/Q^2)F^2$, Q/F) - all that shown individually for saline water, pure fresh water and pure sea water. The rates of flow of each kind of water were calculated from the observed discharge rate and water salinity data.

Therefore, this paper should be addressed not only to mine dewatering experts but also, or even much more, to coastal karst hydrogeologists. The author of the paper (A.Š.) does not know that such a specific and comprehensive exploration has ever been performed in coastal karstic terrains anywhere in the world. Moreover, to his thinking, only a mine with such comprehensive exploration and broad processing can provide such valuable data about the coastal karst hydrogeology aimed at understanding the relationship among the "great quartet" of coastal karst hydrogeology: the rate of groundwater flow, water pressure, water salinity and the hydraulic characteristics of porous media; the last factor includes the discovery of changes in both vertical and horizontal directions.

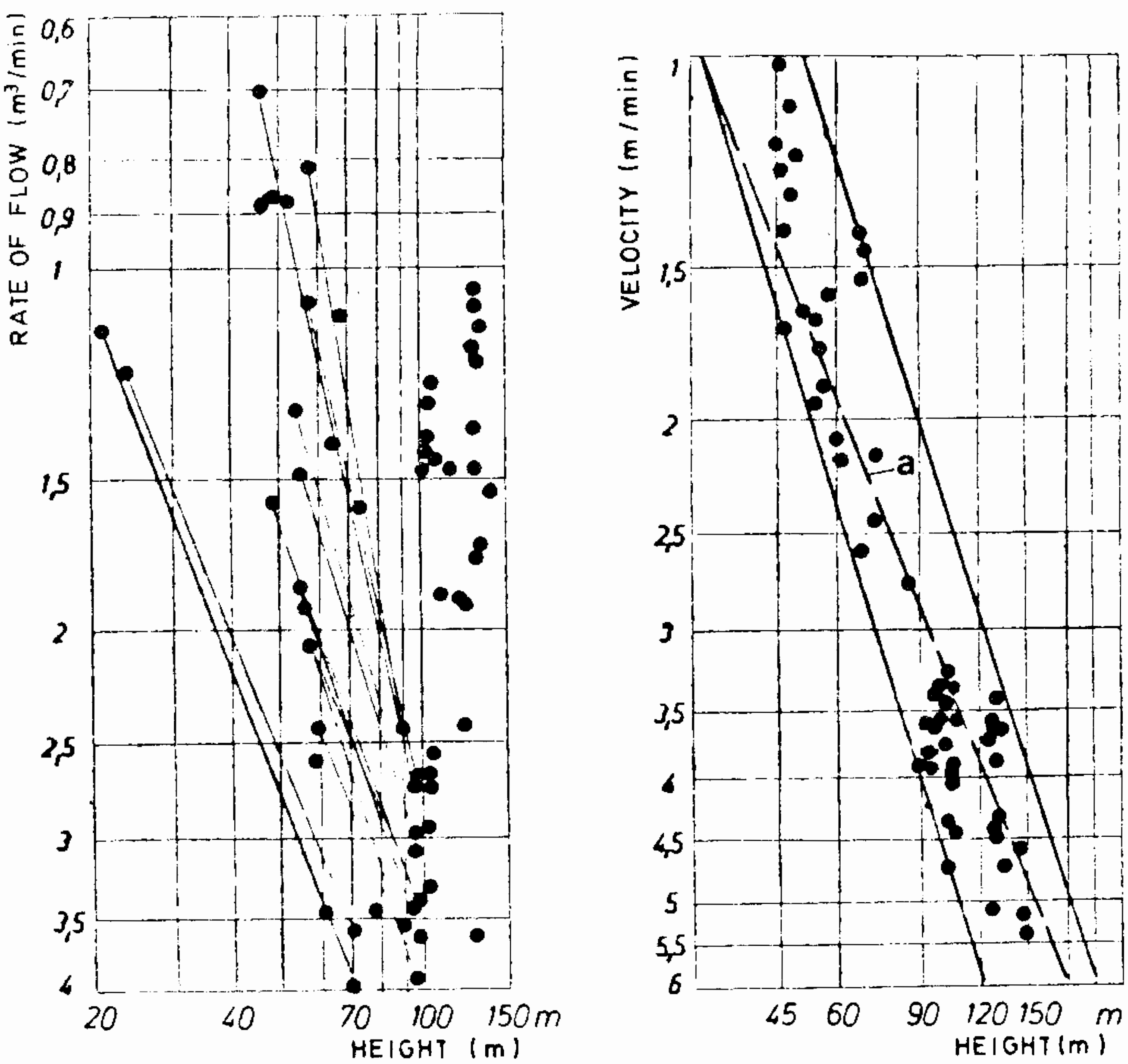

Fig.4 Rate of flow and velocity of pure fresh water (calculated from water salinity) in dependance on water height (after Baturić)
a - laminar flow curve

The next reason of dealing with the discussed matter is the desire to pay homage, for his work, to the late Josip Baturić, during decades professor of applied geophysics and also of mining surveying at the University of Zagreb, a mining engineer and Ph.D. in mathematics. The awareness of an experienced engineer and researcher, although he was not familiar with the necessary details in theoretic hydraulics (he studied them during the considered exploration) was admirable. This awareness enabled him to believe that the planned test discharges would be harmless and the final goal - the dewatering of the mine field 5 - would be feasible and profitable. We must remember that those discharges were carried out under very high rates of groundwater flow deep underground, close to the sea coast, and 140 m below sea level, so also under 14 atm of initial water pressure; all that in an old semi-abandoned, long and narrow, hardly passable mine gallery.

Baturić was courageous to do all that, he managed to convince the directors of the Raša mine to let him perform all that work and was able to carry it out and interpret the exploration.

REFERENCES

1. Baturić J. Problemi "Kaverne" u Raši (Problems of the Kaverna in Raša). Krš Jugoslavije, 3, pp. 107-131 and 17 tables of figures, Zagreb (1962).