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On the Geoelectro-Geohydraulic Analogy Research Project in the River Plains of Northern Croatia

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Key words: Electro-hydraulic analogy, Hydraulic conductivity index, Transmissivity index, Leakage index, Alluvial aquifer, Covering aquitard.

Ključne riječi: elektro-hidraulička analogija, indeks hidrauličke vodljivosti, indeks transmisivnosti, indeks procjeđivanja, aluvijalni vodonosnik, polupropusni pokrov.

Abstract

The use of the electro-hydraulic analogy, i.e. the hydraulic conductivity-electric resistivity relationship, is a very rational applied hydrogeological method for the exploration of loose fluvial and lacustrine clastics saturated with fresh groundwater of a commonly low salinity. The geohydraulic parameters: hydraulic conductivity, transmissivity and leakage coefficient are substituted by their apparent counterparts: hydraulic conductivity index, transmissivity index and leakage index calculated from resistivity sounding data.

This method cuts exploration costs considerably and can be applied to solving several important water management problems related to horizontal and vertical groundwater flow, particularly for aquifer modelling and groundwater quality protection in areas of developed agriculture. The paper presents the initial thoughts, hypotheses and research approaches of a current research project being carried out in the Republic of Croatia.

Sažetak

Korištenje elektro-hidrauličke analogije, tj. odnosa hidrauličke vodljivosti i električne otpornosti, vrlo je racionalna primijenjeno hidrogeološka metoda istraživanja nevezanih riječnih i jezerskih klastita zasićenih podzemnom vodom uobičajene, male slanosti. Geohidraulički koeficijenti: hidraulička vodljivost, transmisivnost i koeficijent procjeđivanja zamjenjuju se njihovim približno točnim protuveličinama: indeksom hidrauličke vodljivosti, indeksom transmisivnosti i indeksom procjeđivanja, koji se računaju pomoću podataka geoelektričnog sondiranja.

Ovom se metodom znatno smanjuju troškovi istraživanja, a ona može biti primijenjena za rješavanje nekoliko važnih vodno gospodarskih problema vezanih uz horizontalni i vertikalni tok podzemne vode, i to naročito za modeliranje vodonosnika i pri zaštiti kvalitete podzemne vode u područjima s razvijenom poljoprivredom. U članku se izlažu početne spoznaje, hipoteze i znanstveno metodološki pristupi jednog aktualnog istraživačkog projekta koji se izvodi u Republici Hrvatskoj.

1. INTRODUCTION

The objective of this paper is to inform the water management and hydrogeological community about the current research project: "Mapping of Geohydraulic Parameters by means of Resistivity Sounding". The project is being carried out by hydrogeologists of the Institute of Geology, Zagreb and by several collaborating specialists. The relationship between the apparent geohydraulic parameter, the so-called hydraulic conductivity index and electrical resistivity will be determined in some ten pilot areas in large lowlands of northern Croatia within the first, experimental, stage of research (Fig. 1). The second stage deals with the use of the obtained relationship to calculate and map two controlling apparent geohydraulic parameters, transmissivity and leakage indices, on the basis of which several water management problems related to horizontal and vertical groundwater flow might be solved at low cost. The most provocative application relates to its use for groundwater protection or, more specifically, to "environmentally restrained" developed agriculture in large river plains of moderate climate all over the world. The research project, which should be completed by December 1995, is financed to a limited extent by the Ministry of Science and Technology of the Republic of Croatia (Project No. 2-04-167).

2. PROBLEM AND OBJECTIVES

The ever-increasing use of groundwater for water supply and its ever-increasing actual or potential pollution makes the exploration and use of groundwater more and more complex and expensive. There is a strongly argumented opinion that, by applying this combined applied hydrogeological and geophysical exploration method within the domain of electro-hydraulic analogy, those costs might be dramatically decreased.

It is necessary to find a reliable relationship between a geohydraulic parameter, hydraulic conductivity, and a geoelectric parameter, electrical resistivity, for loose sediments saturated with groundwater. Furthermore, on the basis of that relationship and relatively inexpensive resistivity sounding, two important geohydraulic indexes, i.e. apparent geohydraulic parameters, which may serve as substitutes for the aquifer transmissivity and

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leakage coefficient of the covering aquitard, can be calculated and mapped.

3. PREVIOUS RESEARCH

Connections between the hydraulic conductivity of clastic sediments and their resistivity (or, stated more fully, the apparent specific electrical resistivity) was known to the geophysicists who were engaged in the electrical logging of wells (ARCHIE, 1942; SCHLUMBERGER, 1970 CROFT, 1971). Limited research of available references on this topic showed that for about the last 25 years there have been a number of attempts to use geoelectric data for approximate determinations of geohydraulic parameters, such as aquifer hydraulic conductivity and transmissivity (VAN DAM & MEULENKAMP, 1967; PFANNKUCH, 1969; ARANĐELOVIĆ, 1969/70, DUPRAT et al., 1970; ZOHDY et al., 1974; KELLY, 1977; MAZAC & LANDA, 1979; KOSINSKI, 1981; ALLESSANDRELLO & LEMOINE, 1983; KELLY & FROHLICH, 1985; HUNTLEY, 1986; AHMED et al, 1988). However,a Soviet researcher who dedicated his book entirely to the electro-hydraulic analogy (DRUZHININ, 1966) listed an incredible number of 231 references of which 165 had been published in the former Soviet Union. Most of the references related to this analogy; the first ones were published some 70 years ago (PUPPINI, 1922; RELF, 1924). No doubt more efforts on the electro-hydraulic correlation have been made throughout the world since the preparation of this book.

The project initiator, through his initial professional involvement in geoelectric exploration for groundwater as a geophysicist, and later work as a hydrogeologist, has been interested in various applications of geophysical exploration for hydrogeological purposes. Since 1965, he has returned several times to various aspects of the electro-hydraulic analogy developing independently his approach to this applied hydrogeological method (ŠARIN et al., 1978; ŠARIN, 1990). Estimation of the approximate leakage of covering aquitards by means of their resistivity and its application has not yet been discussed (to the authors' knowledge) in the scientific literature.

4. THE THEORY

The research project is based on the known fact that the electrical resistivity, ρ, of loose sediments saturated with groundwater of a commonly low salinity reflects their hydraulic conductivity, K. The greater the resistivity the greater the hydraulic conductivity according to an exponential relationship. Both parameters exhibit an inverse relationship with the amount of the very fine-grained fraction of the sediments, and their clay content. In order to emphasize the approximation and origin, the name, symbol and unit of the hydraulic conductivity, K, have been changed to indicate that it was obtained by means of resistivity sounding. It became the hydraulic conductivity index, κ, its unit is HCI and has the dimensions LT^{-1}; while, in fact, 1 HCI = 1 m/day (ŠARIN, 1990).

Two principal geohydraulic parameters controlling the horizontal and vertical groundwater flow: transmissivity, T, and leakage coefficient, L, have also undergone the same formal changes if calculated on the basis of apparent parameter κ. They are substituted by the transmissivity index, τ, and the leakage index, λ, and their units are TI and LI being approximately equal to m^2/day and day^{-1}, respectively. Their mathematical expressions are identical to those of their more exact counterparts. Thus, for a one-layer aquifer and covering aquitard: $\tau = \kappa m$ and $\lambda = \kappa/m'$, while for a multilayer aquifer and aquitard:

$$\tau = \sum_{i=1}^{n} \kappa m_i \quad , \text{ and } \quad \lambda = 1 / \sum_{i=1}^{n} m'_i / \kappa_i \quad ,$$

where m is the aquifer thickness and m' is the covering aquitard thickness. Having no better solution at present, both the horizontal and vertical hydraulic conductivities, K and K', although different in magnitude, are substituted by only one apparent parameter, a common hydraulic conductivity index, κ.

5. RESEARCH PROCEDURE

The first step was to find an initial κ-ρ curve by which the resistivity data can be converted into κ values. Such a curve was determined by the project initiator in 1965 as a by-product of a complex hydrogeological exploration carried out at Hutovo Blato, near the river Neretva, in Herzegovina (ŠARIN, 1990). The curve was prepared on the basis of a dense network of shallow resistivity soundings, a great number of grain size analyses of samples collected from numerous shallow boreholes, and earlier laboratory measurements of permeability.

The next stage of research consists of the determination of κ-ρ curves valid for the pilot research areas in northern Croatia. This is being achieved by a method known in aquifer modelling as calibration. Namely, τ values obtained from ρ values of the screened depth intervals in the wells of those areas by means of the initial κ-ρ curve of Hutovo Blato are compared with the corresponding T values which were obtained from pumping tests in the wells. These τ and pertaining T values will not perfectly correspond to each other. A random-like arrangement of the τ/T points along several straight or gently curved lines in a τ-T diagram is much more probable. Through the calibration procedure, the obtained lines will be used to modify the initial κ-ρ curve until several new, so-called standard, κ-ρ

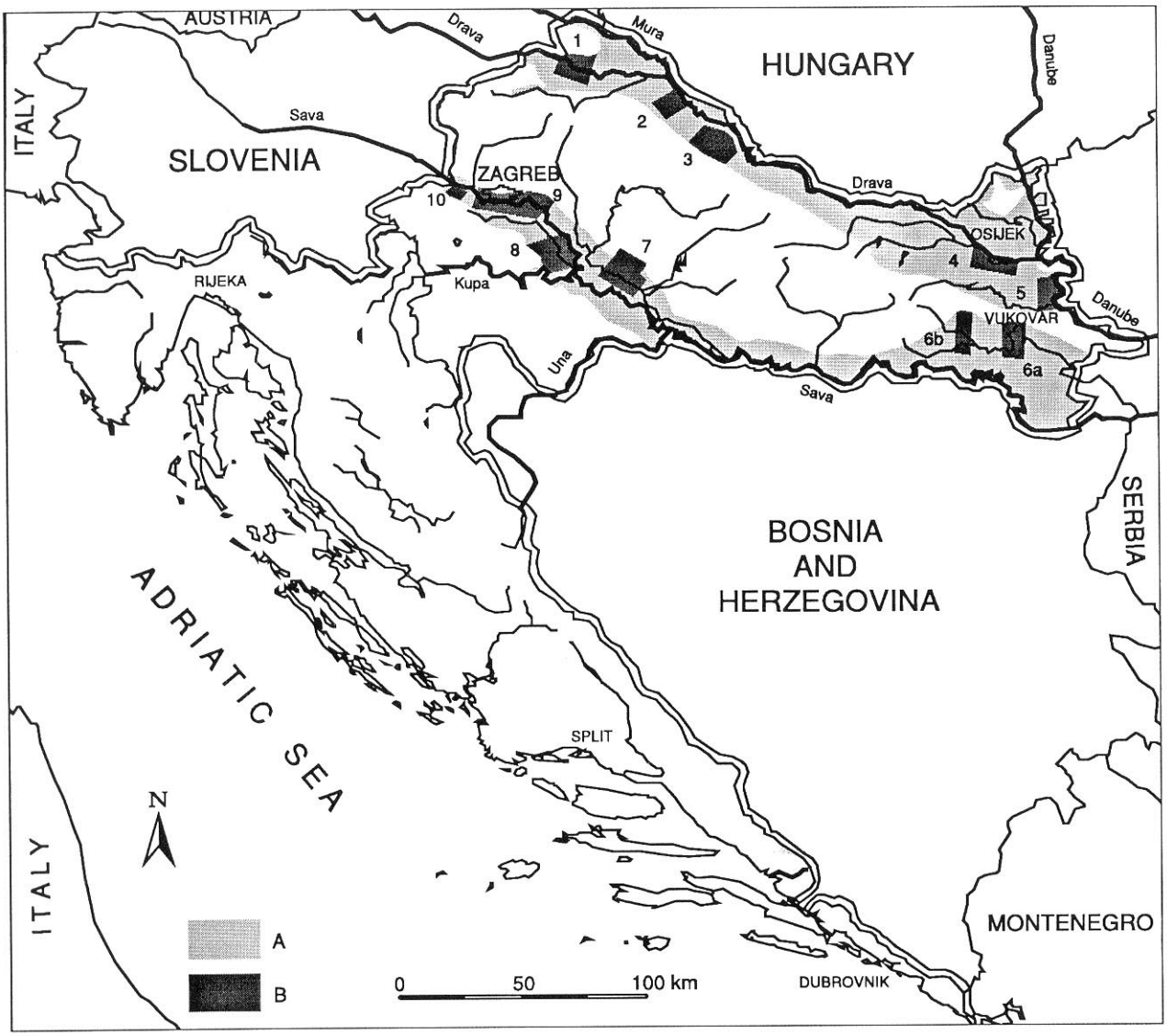

Fig. 1. Situation of pilot research areas in northern Croatia A - Large river plain, B - Pilot research area, 1 - Varaždin, 2 - Koprivnica, 3 - Đurđevac, 4 - Osijek, 5 - Vukovar, 6a -Vinkovci, 6b - Đakovo, 7 - Ravnik-Kutina, 8 - Sisak, 9 - Zagreb, 10 - Samoborsko polje.
Sl. 1. Položaj istraživačkih pilot-područja u sjevernoj Hrvatskoj A - Prostrana rječna ravnica, B - Istraživačko pilot- područje.

curves are found and accepted as accurately representing the κ-ρ relationship in each pilot area (Fig. 1).

The discussed calibration refers to the horizontal groundwater flow only. For the analogy in the vertical groundwater flow domain, represented by the λ-L relationship, in northern Croatia there are less field data for calibration than for τ-T relationship. For several pilot areas, their aquifer models with the defined infiltration of precipitation will be very useful in determining the leakage coefficient.

In the first stage of the research project, κ values will be determined for all ρ values of the resistivity sounding stations occurring within the pilot areas. This will be done by means of the accepted standard κ-ρ curves. From the obtained κ values, the parameters τ and λ will be calculated for each sounding station and maps, showing the distribution of these indices, will be prepared for all the pilot areas.

6. APPLICATION AND LIMITATIONS

By using the considered applied hydrogeological method, the whole or a part of the resistivity curve of a resistivity sounding station, with all its data on resistivities and pertaining thicknesses, is substituted by a single numeral. This numeral represents a natural, geohydraulic, magnitude. A map containing these numerals is a useful tool in hydrogeological exploration. Even if these numerals had only qualitative, i.e. relative, significance, the maps could still be useful because areas having similar values of the calculated apparent parameters might be separated. In certain cases, the areas classified in more detail - as the areas having very high, high, medium, low, very low values of these parameters - might be outlined. However, since the discussed numerals have also a rather high quantitative significance, such maps should be even more useful.

If there is a sufficient number of resistivity sounding measurements and if they are spread over large enough areas, the maps showing the distribution of the parameter τ may be used for the solution of problems related to horizontal groundwater flow, such as in locating optimal sites for production wells, in aquifer modelling and in delineating sanitary protection zones of pumping sites. The maps showing the distribution of the parameter λ may be used to gain a better understanding of groundwater vertical flow conditions in large plains and, thus, can be applied as a useful tool in the delineation of the protection zones of pumping sites, in estimating the infiltration of precipitation and estimates of the "admissible" contaminating load in agricultural areas. The last objective relating to agricultural pollution is an intriguing issue, particularly for areas of highly developed agriculture.

Under extremely favourable conditions, by using the electro-hydraulic analogy in horizontal groundwater flow applications, several resistivity sounding station might be used instead of a test-pumped drilled well. The costs could be lower by a factor of up to several tens. Within the vertical groundwater flow applications, the costs cannot be reduced below one tenth. Under common conditions, the differences are smaller. However, the exploration expenses are considerably lower if already existing resistivity explorations are used. In northern Croatia, there are many areas covered by a great number of resistivity sounding stations used within exploration for various petroleum, hydrogeological, engineering geological or mining purposes.

It is, nevertheless, necessary to bear in mind that the considered applied hydrogeological method has certain limitations. First of all, the considered segment of the electro-hydraulic analogy or, more precisely, the existence and accuracy of the κ-ρ relationship are valid only under the following basic hydrogeological conditions: (1) the sediments are loose clastics, (2) the sediments are saturated with groundwater, (3) the groundwater is commonly of low salinity, particularly of a very low sodium chloride content. In addition to these major factors which decisively control the κ-ρ relationship, there are also several minor factors that must also be taken into account. These include the substantial homogeneity of the following groundwater and rock properties within the explored areas: (1) groundwater salinity, particularly sodium chloride content, (2) rock porosity, (3) basic petrology, (4) coefficient of uniformity of grain sizes. There is also a set of geoelectric constraints derived mostly from certain inaccuracies of the resistivity sounding data themselves.

In conclusion, concerning the major controlling factors, we may say that favourable conditions exist in almost all lowland plains filled with fluvial and/or lacustrine deposits in the whole of the moderate climate zone all over the world. As far as the minor controlling factors are concerned, it may be said that they have mainly negligible effects if large explored areas are divided into smaller sections each researched separately. As far as the geoelectric constraints are concerned, it is the authors' pleasure to state that they have only a minor influence in northern Croatia. That is to say, most of the resistivity sounding of that region was performed by the "Geofizika" company of Zagreb, which did it very thoroughly.

7. INTERNATIONAL COOPERATION

The project was conceived as a national one focused only on the areas of northern Croatia where the wide valleys of major European rivers (the Danube, Sava and Drava) form the southwestern flank of the vast central European Pannonian sedimentary basin.

Meanwhile, the obvious advantage of international cooperation led the researchers to offer such a form of research to the international scientific community. Interest has been shown by six prominent institutes in the Netherlands, Germany, Hungary, Austria and Italy. The level of cooperation could range from an exchange of references and experience to carrying out similar research in other areas of Europe where the hydrogeological conditions are suitable and an adequate technical basis exists: a resistivity sounding network and test pumped wells.

The component of this research project related to the vertical groundwater flow or, more precisely, to the use of the discussed exploration method in defining hydrogeological aspects of actual or potential agricultural pollution, forms a contribution from the Institute of Geology, Zagreb to a current European research project. This is COST Action 66, "Pesticides-Soil-Environment", within the Commission of European Communities, carried out predominantly by French and other European biochemists.

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