SLOVAK GEOLOGICAL MAGAZINE

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Hydraulic Parameters of Sediments of the Inner Carpathian Paleogene in Eastern Slovakia

Influence on Land Use on Water Quality in Mountainous Areas – A Case Study from Slovakia

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Geochemical Atlas of Slovakia – Groundwaters, Preliminary Results

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Mapping Critical Loads/Exceedances: Natural Waters of Slovakia

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Foreword

The Dionýz Štúr Institute of Geology (GÚDŠ) in Bratislava, since it had been founded in 1940 (as the State Institute of Geology), contributed substantially to the study of Western Carpathian geological structure, as well as the development of applied geological disciplines in Slovakia.

Extensive co-operation of the Institute within our country as well as abroad was a guaranty of providing geological information from the Slovak territory on a level acceptable to the wide geological public.

Changes to which geology in Slovakia has been subjected since 1989 in connection with the transition from central planning to market economy require fundamental changes also in the editorial activities of GÚDŠ. A priority task is considered to be the transition from extensive to intensive activity in this area, i.e. to produce less journals, periodicals, proceedings etc., but in higher quality, focusing on foreign-language versions.

The position of GÚDŠ in the Forum of European Geological Surveys - FOREGS - and the exceptionally extensive co-operation with foreign geological institutions in various international geological programmes, especially within IGCP, literally forced us to reduce the production of all-Slovak versions of geological journals and to focus on the English version of a periodical, which would promptly and in sufficient extent inform the international public about geological activities in Slovak Republic, especially on the level of national geological surveys. Therefore, we decided to publish since 1995 four times in a year the geological periodical

Slovak Geological Magazine.

In this respect, the structure of important Slovak geological periodicals, as compared with abroad, may be generally considered to be optimum. Besides internationally well established journals, Geologica Carpathica and Mineralia Slovaca, the geological public is obtaining in English wide-range information on the latest results of regional geological studies and the results of applied disciplines (hydrogeology, hydrogeothermy, engineering geology, environmental geochemistry etc.) from the territory of Slovakia.

It is not by chance that the first issue of the Slovak Geological Magazine is dedicated mostly to hydrogeology and hydrogeochemistry, since the development of these disciplines (in regional as well as topical sense) attained at GÚDŠ an internationally acknowledged standard. This issue is presenting above all the results of hydrogeological investigations focused on synthetic interpretations, based also on results of previous regional surveys. For the information of foreign specialists it is has to be mentioned that basic hydrogeological characterisation of the Slovak territory has been published in English the monothematic issue of the journal of GÚDŠ "Západné Karpaty", No.8, series "Hydrogeológia a inžinierska geológia" in 1989. The publication can be obtained from the library of GÚDŠ. Some of the next issues of the Slovak Geological Magazine will be also monothematic, it is however not the principal and long-term intent of the publishers.

I am convinced that this first issue of Slovak Geological Magazine, the new geological periodical from Slovakia, will mark the right course and that it will become a useful partner of foreign specialists, providing them with results of Slovak geologists.

I wish the Slovak Geological Magazine a lucky journey and a lot of success in future.

RNDr. Kamil Vrana, CSc.
Director of Dionýz Stúr Institute of Geology

Contents

Utilizing Data on Specific Capacities of Wells and Water- Injection Rates in Regional Assessment of Permeability and Transmissivity

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Abstract.

Specific capacities from aquifer tests and water injection rates from water injection tests can be utilized for getting a true picture of spatial distribution of rock hydraulic properties even from less accurate and incomplete archival data inapplicable to an exact determination of hydraulic coefficients e. g. by straight-line method. After transformation to the approximative logarithmic parameters – permeability index Z and transmissivity index Y - the distribution characteristics of Z and Y are converted to the respective estimates of hydraulic conductivity and transmissivity. The conversion is simplified to the problem of an optimum estimate of the conversion difference than can be constructed analytically as a function of storativity, test time and well radius or found by analogy. The suggested procedure has proved its utility at regional hydrogeological research in many regions of various types.

Key words: hydrogeology, permeability, transmissivity, hydraulic conductivity, statistical evaluation, aquifer tests, water injection tests, methods of regional hydrogeology

(1 Fig., 2 Tabs)

At the present state of art, regional assessment of hydraulic properties of rocks is focused on the study of spatial and statistical distribution of permeability and transmissivity. In regional assessment, the number (density) of data is substantially more important than the absolute accuracy of the information on the hydraulic parameter value at an individual point of the studied space. To get a complete objective picture of the hydraulic properties of rocks on a regional scale, it is therefore indispensable to exploit to a maximum degree all, be it incomplete or less accurate, data on pumping from earlier wells and boreholes and to obtain from these data the necessary information in a way that would be adequate to their degree of accuracy. Such an effort resulted in defining approximative (comparative) logarithmic parameters - the permeability index Z and the transmissivity index Y, which can be determined in all cases where at least data on specific capacity of the well are available. The expression in the terms of such parameters signalizes a lesser degree of accuracy and rules out the risk of confusing the exactly determined hydraulic conductivity coefficient or the transmissivity coefficient with their inaccurate estimates. These parameters may be used advantageously also in a strongly inhomogeneous medium.

The number of wells in which specific capacity could be computed from archival documentation is, as a rule, considerably greater than the number of wells with complete data from aquifer tests making possible a more precise determination of aquifer parameters e. g. by interpretation of transient data. The specific capacity is therefore the starting point for getting sufficiently extensive and detailed information for regional assessment of permeability and transmissivity in hydrogeological practice.

The specific capacity or the ratio of the specific capacity to the length of tested interval was used at regional transmissivity and permeability evaluations by WALTON (1962), WALTON–CSALLANY (1962), ZEISEL et al. (1962), WALTON–NEILL (1963), CSALLANY (1963) and others. WALTON (1962, 1970) presented also charts for estimating transmissivity from specific capacity at selected values of storativity, time and well radius. Other authors studying the correlation between transmissivity T and specific capacity q suggested particular values of the ratio T/q for estimating transmissivity.

Determining specific capacity

The input for the derivation of the approximative logarithmic parameters is the specific capacity q defined as the ratio of the flow rate (withdrawn discharge) Q to the respective drawdown s in the well

$$q = Q/s \qquad (1)$$

Considering generally non-linear relation between Q and s, the discharge Q corresponding to the drawdown of one meter (s = 1 m) is substituted into the equation (1). Under water-table conditions, if only data for drawdown s_n greater than 1 m are available, the theoretical specific capacity q_1 for s = 1 m (standard specific capacity)

$$q_1 = q_n (2M - 1) / (2M - s_n) \qquad (2)$$

is derived (M = initial saturated thickness of an unconfined aquifer, s_n = observed drawdown of water table in the well, q_n = specific capacity calculated for $s = s_n$).

If the drawdown of unconfined water table in the well sw exceeds 1/10 of the initial saturated thickness M, the measured drawdown s_w should be adjusted by the formula (Jacob 1944)

$$s_c = s_w - s_w^2/2M \qquad (3)$$

substituting s_c into the calculations instead of the s_w. At the calculation of standard specific capacity q_1, e. g. according to the formula (2) is s = 1 m. Instead of the standard specific capacity value q_1 from the formula (2) we use in accordance with the correction (3) the adjusted value

$$q_{1c} = q_1 \, . \, 2M/(2M - 1) \qquad (4)$$

as the input specific capacity in calculating the approximative logarithmic parameters for a water-table aquifer.

In calculating the index Z, we could alternatively replace the correction (3) and (4) with a correction of the thickness M and substitute the corrected thickness

$$Mc = M - s_w/2 \qquad (5)$$

e. i. in the case for s = 1 m and M less than 10 m

$$Mc = M - 0.5 \text{ (m)} \qquad (6)$$

instead of the unaffected thickness M. As a matter of course, the uncorrected value of q_i is used in such a case.

At confined aquifers, the relationship between Q and s is linear up to certain drawdown. For greater drawdowns this relation is, however, non-linear even here. If a sufficient number of points for constructing the curve Q = f(s) is available, the standard specific capacity q1 is determined by a graphic extrapolation up to s = 1 m. If such an extrapolation is impossible, we estimate the standard specific capacity by a parabolic approximation, applying the relation (2) in the form

$$q1 = qn \, . \, (2H - 1)/ (2H - sn) \qquad (7)$$

where H = the height of the static level above the lower limit of the tested interval (Jetel 1993b) [q_n and s_n as in (2)]. This approximation is only a rough estimate of an unknown non- linear course of the curve Q = f(s). Nevertheless, it makes possible an objective reproducible correction of the decrease of specific capacity with drawdown.

Expressing the discharge Q in the formula (1) in $m^3 \, . \, s^{-1}$ and the drawdown in meters, the specific capacity is expressed in $m^2 \, . \, s^{-1}$. If we express the discharge in liters per second, the specific capacity will be expressed in liters per second per metre ($l \, . \, s^{-1} \, . \, m^{-1}$). In such a case the distinctive symbol qo is used.

Approximative logarithmic parameters

The approximative logarithmic parameter of permeability derived from specific capacity is the permeability index Z (Jetel 1964, 1968, 1974)

$$Z = \log(10^9 \, q/M) = 9 + \log(q/M) \qquad (8)$$

$$\text{or} \quad Z = \log(10^6 \, q^o/M) = 6 + \log(q^o/M) \qquad (8a)$$

where q = standard specific capacity in $m^2 \, . \, s^{-1}$, q^o = standard specific capacity in $l \, . \, s^{-1} \, . \, m^{-1}$, M = aquifer thickness in meters. With partially penetrating wells or in the case of an impossible or indefinite determination of the thickness M (e. g. in a fractured rock massif without distinct delimitation of aquifers) a substitutive parameter - the permeability index of the open interval

$$Z_L = \log (10^9 \, q/L) = \log (10^6 \, q^o/L) \qquad (9)$$

is used (L = the length of the open interval in the well below the static level).

At water-table aquifer with the thickness less than 10 m the corrections (4) or (6) are to be applied for the formulae (8) and (8a).

In a partially penetrating well, M is greater than L so that Z_L is greater than the value of Z from Eq. (8) that would be measured in a fully penetrating well. Let us mark the value of Z in fully penetrating well by Z_M, qL being the actual specific capacity substituted into Eq. (9). The symbol q_M will then indicate the theoretical specific capacity of fully penetrating well. Thus,

$$Z_M = \log (10^9 q_M/M) \qquad (10)$$

If the inflow from the more distant unopened parts of an aquifer - in the extent greater than 3L - into the partially penetrating well is considered negligible, the theoretical value of Z_M is estimated as

$$Z_M = (4 Z_L - 0.48) / 4 \qquad (11)$$

(JETEL , 1993b). The formula presented by TURCAN (1963)

$$q_L / q_M = b\left[1+7\sqrt{r_w / 2bM} \,.\, \cos (b\pi / 2) \right] \qquad (12)$$

where b = L/M, r_w = well radius, can be used for a more precise estimation. The value q_M is then substituted into Eq. (10).

The transmissivity index Y (JETEL – KRÁSNÝ 1968, JETEL 1974)

$$Y = \log (10^9 q) = 9 + \log q \qquad (13)$$

$$\text{or } Y = \log (10^6 q^o) = 6 + \log q^o \qquad (13a)$$

representing a logarithmic transformation of specific capacity is the approximative parameter of transmissivity. From eqs. (8) and (13) it follows that for fully penetrating wells

$$Z = Y - \log M \qquad (14)$$

For partially penetrating wells with L smaller than M is the value Y from Eq. (13) an indication of certain effective transmissivity at the particular penetration degree and does not correspond to the total transmissivity of the aquifer at fully penetrating well. Provided that the permeability in the whole thickness M is roughly uniform, the representative value of the Y_M can be estimated from the specified Z_M value as

$$Y_M = Z_M + \log M \qquad (15)$$

Logarithmic transformation of hydraulic conductivity k and transmissivity coefficient T (Jetel 1979)

$$Z_k = 9 + \log k \qquad (16)$$

$$Y_T = 9 + \log T \qquad (17)$$

(T in $m^2 . s^{-1}$, k in $m . s^{-1}$) and antilogarithmic transformations of the indices Z and Y (JETEL, 1985ab)

$$k_Z = \text{antilog} (Z - 9) = 10^{(Z - 9)} \qquad (18)$$

$$T_Y = \text{antilog} (Y - 9) = 10^{(Y - 9)} \qquad (19)$$

facilitate a direct comparison of the approximative logarithmic parameters with the exact hydraulic parameters on a common scale.

Logarithmic conversion difference

The parameters Z and Y are simple functions of the specific capacity. Hence, the estimation of exact hydraulic coefficients may make use of the relation between transmissivity T and specific capacity q that may be expressed in terms of the logarithmic conversion difference (Jetel 1979, 1985 ab)

$$d = \log T - \log q \qquad (20)$$

$$\text{e. i. } T/q = 10^d \qquad (21)$$

with T and q in the same units. The first solution converting the indices Z and Y to hydraulic conductivity and transmissivity at transient flow presented by Carlsson and Carlstedt (1977) by introducing a coefficient related to the difference from Eq. (20) as follows

$$\alpha = 10^{-d} \qquad (22)$$

Comparing Eqs. (20) and (13), we see that the relation between transmissivity coefficient T and transmissivity index Y is expressed as

$$T = \text{antilog} (Y+d-9) = 10^{(Y+d-9)} \qquad (23)$$

(T in $m^2 . s^{-1}$). A parallel relation

$$k = \text{antilog} (Z+d-9) = 10^{(Z+d-9)} \qquad (24)$$

applies to the hydraulic conductivity k expressed in meters per second.

A logical consequence of the combination of Eqs. (17), (20) and (23) is the relation

$$d = YT - Y \qquad (25)$$

The introduction of the conversion difference simplifies the estimation of the hydraulic coefficients from the specific capacity to the problem of an optimum estimate of an additive quantity - the conversion difference d.

Basic (primary) conversion difference for an ideal well

A fundamental component of the total conversion difference d in Eqs. (20) – (25) is the difference between log T and log q for particular calculation conditions on the assumption of an ideal well without any well loss (e. i. without any additional hydraulic resistance to the flow into the well and within it). We have termed this component the basic (primary) conversion difference d_o.

Under steady-state flow conditions, the Dupuit's formula implies that the basic conversion difference is given by (JETEL, 1982)

$$d = \log [\log (r_d/r_w)] - 0.436 \qquad (26)$$

where r_d is depression cone radius and r_w well radius. For non-steady state flow fulfilling the conditions of the Cooper–Jacob logarithmic approximation validity (COOPER–JACOB, 1946), the following relationship may be derived (JETEL, 1985 ab):

$$d_o = \log [0.183 - \log \ (2.25\, dt/r^2w)] \qquad (27)$$

where

$$D = T/S \qquad (28)$$

(D = hydraulic diffusivity in $m^2 . s^{-1}$, T = transmissivity in $m^2 . s^{-1}$, S = storativity, t = time after pumping started determining the radius of test influence at the particular moment). Hydraulic diffusivity D is estimated from preliminary assessment of T – e . g. by the TY from Eq. (19) - and from the expected range of storativity. The storativity S of a confined aquifer is computed from the estimate of specific elastic storativity S_s as

$$S = S_s . M \qquad (29)$$

(S_s in m_{-1}). The specific storativity S_s is estimated by Tab. 1 or by the formula

$$S_s = \rho g\, (mo_c w + c_r) \qquad (30)$$

where ρ = water density, g = gravitational acceleration, m_o = open porosity, c_w = water compressibility, c_r = bulk compressibility of rock skeleton. The time t in Eq. (27) is the time elapsed from the beginning of the test up to the instant for which specific capacity was measured. The r_w is the actual inner radius of well. In unconfined aquifer, the water-table storativity (specific yield) can be estimated at S = 0.24 for gravel and coarse sand, 0.22 for medium sand, 0.19 for fine sand, 0.15 for silty sand and 0.05 - 0.15 for loamy sand (MUCHA – ŠESTAKOV, 1987). In the near-surface zone of fractured rocks the values S = 0.02–0.05 may be recommended.

Eq. (27) is valid only before boundary effect or leakage appears. After the depression cone reached a recharge boundary,

$$r_d = 2\, x_b \qquad (31)$$

where x_b is the distance of the well from the recharge boundary, is substituted into Eq. (26). If leakage effect is assumed, we substitute

$$r_d = 1.12 \sqrt{TM \ / k} \qquad (32)$$

(M' = aquitard thickness, k' = vertical hydraulic conductivity of aquitard, T = estimated transmissivity of aquifer) into Eq. (26).

Additional conversion difference

Under real conditions the total conversion difference d from Eq. (25) should be understood as the sum of the basic and additional differences

$$d = d_o + d_a \qquad (33)$$

The additional difference d_a expresses the deviation of actual conditions from the ideal well model. It represents the well loss, in other words the sum of differences caused by additional flow resistances arising close to the well screen, on the screen and inside the well. Theoretically it may be itemized into partial differences of various origins:

$$d_a = d_S + d_L + d_C + d_X$$

where d_S is skin difference, d_L = difference due to partial penetration, d_C is turbulent flow differencey and d_X comprises other unidentified differences. The skin difference d_S reflects the resistance corresponding to the skin effects s. l. (VAN EVERDINGEN, 1953, EARLOUGHAR, 1977) e. i. the changes in permeability in the near-well zone, the reduction of flow entrance area on the well screen etc. The difference d_L corresponds to the effect of partial penetration

$$d_L = \log(q_M/q_L) \qquad (35)$$

[qM determined e.g. by Eq. (12)]. It can be, however pre- eliminated at calculating the Z-value by Eqs. (10) – (12). The difference d_C due to the flow turbulence expresses the effect of the quadratically nonlinear resistance, mainly the turbulence within the well. It is of importance at discharges reaching tens and hundreds liters per second. It may be approximated as

$$d_C = \log \frac{\text{antilog } d_o + Q/r_w T^{0.25}}{\text{antilog } d_o} \qquad (36)$$

(antilog x = 10^x, Q = discharge, r = well radius, T = transmissivity). The formula has been derived (Jetel, 1985ab) from generalized empiric data given by CARLSSON–CARLSTEDT (1977) and GUSTAFSON (1974).

Analyzing the distribution of the Z and Y values

After computing individual values of permeability and transmissivity indices, we turn to statistical analysis aimed at determining the statistical characteristics of the distribution of Z and Y values in data populations corresponding to particular lithostratigraphic units, rock types or regions, first of all, minimum and maximum values, medians Md, sample arithmetic means M(Z) or M(Y) and sample standard deviations s_Z and s_Y with the estimates of general population standard deviations are to be determined. The statistical significance of the stated differences in sample means should be tested as well. It is necessary to delimitate the confidence intervals within which are located the true (population) means with the specified probability.

Simultaneously with the computation of the characteristics mentioned above it is useful to visualize the identified distribution by histograms and quantile (frequency) graphs (JETEL, 1985a). The quantile graph (cumulated relative frequencies graph) makes it possible to asses the conformity of the displayed data with the normal distribution model. If the graph indicates pronounced deviations from the normal model, it is necessary to verify the relevance of the extreme values to the studied population and to decide if the apparently homogeneous set of data is not an intersection of two or more subsets with theirs own distributions that must be studied separately.

An illustrative confrontation of individual data sets is possible by the "box-and-whisker plot" (e. g. GUSTAFSON–KRÁSNÝ 1994, JETEL, 1994, JETEL–VRANOVSKÁ, 1995) for which quartile values are to be computed.

After expressing the statistical characteristics of the distribution of approximative parameters Z and Y, these characteristics are to be transferred to the corresponding distribution characteristics of non-logarithmic hydraulic coefficients – hydraulic conductivity k and transmissivity T. After adequate transformations, the minimum and maximum values of the estimates of k and T as well as the medians Md(k) and Md(T) correspond directly to the minimum, maximum and median values of Z and Y. By contrast, it is the geometric mean of a non-logarithmic coefficient that is the statistical characteristic corresponding to the arithmetic mean of a logarithmic parameter:

$$G(k) = \text{antilog } [M(Z)+d-9] = 10[M(Z)+d-9] \quad (37)$$

$$G(T) = \text{antilog } [M(Y)+d-9] = 10[M(Y)+d-9 \quad (38)$$

where G(k), G(T) are geometric means of the respective coefficients, M(Z), M(Y) = arithmetic means of the indices Z and Y, d = total conversion difference. Normal (Gauss) distribution of the logarithmic parameters (Z, Y or other logarithmic transformations) indicates lognormal (Galton) distribution of the respective non-logarithmic coefficients (k, T). The variability is characterized also here by the standard deviation of logarithmic parameters (s_Z, s_Y) as it is practically identical with the standard deviation of non- logarithmic parameter logarithms (slog k, slog T).

The choice of the averaging method of individual k and T values depends on several factors. Large-scale permeability tests (WITHERSPOON et al., 1980, GUSTAFSON et al., 1989, GALE et al., 1989, BROCH–KJORHOLT, 1994) show that the geometric mean of permeability values determined from borehole tests agrees reasonably well with bulk rock mass permeabilities determined during macropermeability experiments. From this point of view, the geometric mean should considered as a true characteristic of mean permeability and transmissivity (cf. JETEL, 1985a). Yet where one-dimensional flow in a series connection of flow segments is assumed, it is the harmonic mean that conforms best to the effective permeability and transmissivity of such a series. In statistically homogeneous medium with lognormally distributed permeabilities, the geometric mean expresses according to GUTJAHR et al. (1978) and DAGAN (1979) the effective permeability for 2-dimensional flow while for 3- dimensional flow it is the effective mean

$$Ef(k) = G(k) \,.\, [1 + s^2_{\ln k}/6] \;-\; G(k) \,.\, [1 + 0.884\, s^2 \log k] \qquad (39)$$

If it is impossible to measure with confidence and to express quantitatively permeabilities smaller than a certain lower limit and an accepted minimum value is consequently substituted into the calculations, the geometric mean becomes overestimated and the median value will be its optimum estimate (BROCH–KJORHOLT, 1994).

Since the permeabilities (hydraulic conductivities) and transmissivities are, as a rule, distributed lognormally, there is still another characteristic of their mean value – the mathematical expectance of lognormally distributed values

$$EL(x) = G(x) \,.\, \psi n\,(t') \qquad (40)$$

where $$t' = 2.65\, s^2_{\log x} \qquad (41)$$

($s_{\log}$ x = standard deviation of the logs x). It is the mean value with the maximum likelihood for the given distribution, e. i. a hypothetical average generating with the maximum probability the observed empirical distribution. The values of the function are given by AITCHISON and BROWN (1957) (in more detail see JETEL, 1985a). At slog k less than 0.45 the EL (k) is close to the Ef(k) = Ef(x) from (39)

Besides the approximative logarithmic parameters Z and Y derived from specific capacities also the values of hydraulic conductivities k and transmissivities T determined by exact methods – e. g. by straight-line (semi-log) method from transient tests – can be used in the same manner for deriving the regional characteristics of permeability and transmissivity. In such a case, it is suitable to convert the values of k and T by the transformations (16) and (17) to the form compatible with the form of indices Z and Y.

Estimating hydraulic conductivity and transmissivity from the values of Z and Y

For converting Z and Y values to the corresponding estimates of hydraulic conductivity k and transmissivity T we use Eqs. (23) and (24) substituting the appropriate conversion difference d. To determine the difference d, the following procedures are available:

(a) In estimating k and T values from individually found values of Z or Y, the conversion difference is determined analytically – combining calculations by Eqs. (26) and (27) with estimates by analogy.

(b) In estimating the statistical characteristics of the distribution of k and T from calculated characteristics of the Z and Y values distribution, the conversion difference is estimated

(ba) analytically in the sense of (a) for particular minimum, median and maximum values of Z and Y,

(bb) from generalized regional estimates by means of regression equation d = f(Y) derived for particular found or constructed values of d, namely from the average estimates determined

(bba) analytically ad hoc for particular evaluated data,

(bbb) by previous works in the region,

(bc) by analogy with other regions.

The (bb) way is used where the converted values of Z or Y do not represent any actually measured values with data necessary to an analytical construction of d-value (e. g. et converting a computed mean).

At an analytical construction of d, the value of d_o is determined by Eq. (27) or (26). With high discharges from wells of small diameters the difference dC is computed by (36). If the correction on partial penetration has not been applied at calculating Z and Y by Eqs. (10) or (11) and the actual conditions substantiate the use of the partial penetration model, the difference d_L is estimated by (12) or from tables and charts (JETEL, 1985ab). The skin difference d_S cannot be analytically computed. In a first approximation it can be neglected. For a more accurate estimate we use an analogy with the wells in which the actual value of d could be determined from comparing Y with the transmissivity found directly from high quality data (e. g. by the straight-line method). From Eq. (25) the value of d is obtained so that

$$dS = d - d_o - d_C - d_L \qquad (42)$$

Another approximation is possible by substituting systematically a certain small constant value – e. g. $d_S = 0.1$ – for wells of standard construction.

The regional mean estimate of the d-values for a region (a statistically homogeneous set of data) may be derived by computing the regression equation

$$d = a + bY \qquad (43)$$

Such average estimates derived from a particular equation of the type (43) are substituted into Eqs. (23) and (24). As examples, the empiric equations derived for the wells in alluvial aquifers in the Košice basin (Jetel, 1993b)

$$d = 0.07\,Y - 0.29 \qquad (44)$$

for the neovolcanics of the Slanské vrchy Mts. (JETEL, 1993a)

$$d = 0.13\,Y - 0.40 \qquad (45)$$

or for Paleogene in Hornád basin and Spišská Magura Mts. (JETEL – VRANOVSKÁ, 1995)

$$d = 0.23\,Y - 0.94 \qquad (46)$$

can be mentioned. Preliminary estimation of the d-values can be based on the generalized experience from various regions (Tab. 2). The total difference d in the wells in which it has been determined by Eq. (25) ranges from d = -0.30 to +1.15 with scarce exceptions. The highest values of d, da and dS are observed in deep boreholes of mineral deposit exploration in connection with high additional resistances due to mud fluid and imperfect perforation. The experience with the boreholes in the Hornád basin and Spišská Magura Mts. shows that in the intervals tested Tab. 2 The most frequent values of total, additional and skin difference at aquifer tests at first with open unlined wall the covering of the walls by perforated casing (screen) increased the additional difference da by 0.1–0.6 (0.25 on the average).

Interpretation of water injection test data

Water injection tests (pressure tests), originally a geotechnic method to studying rock basement tightness and grouting conditions, afford very useful data for exploring spatial distribution of permeability and are often the sole source of direct information on permeability in mountaineous regions without hydrogeologic boreholes. A direct computation of hydraulic conductivity from individual measured data is problematic with regard to some non-measurable input characteristics. However, for a regional assessment we can easily dispense with assigning a particular value of hydraulic conductivity to each tested interval. An approximative parameter – permeability index of tested interval Z' can be again used conversing the characteristics of its distribution to the corresponding characteristics of hydraulic conductivity.

Water injection rate (the volume of water injected during a time unit) is similarly to Eq. (1) transferred to the specific injection rate

$$g_h = Q_h/s_h \qquad (47)$$

where
$$s_h = p/\gamma + H_h \qquad (48)$$

is elevation of piezometric head in well, p is overpressure on the well orifice, γ is specific weight of water (9.8×10^{-3} $N.m^{-3}$) and H_h is the depth of static level below well orifice (in a non-saturated interval it is the depth of the tested interval base). Similarly to Eq. (9) the permeability index Z' at water injection test is defined as

$$Z' = \log(10^9 q_h/L) = \log(10^6 q^o{}_h/L) \qquad (49)$$

where q_h is specific injection rate from Eq. (47), qoh being expressed in $l\ .\ s^{-1}\ .\ m^{-1}$ after substituting Q_h in liters per second. In the documentation of injection tests the quotient of injection rate Q_h and length of tested interval L is often presented. Instead of q_h/L the quotient Q_h/Ls_h is then substituted into Eq. (49). The value of Z' from Eq. (9), yet with changed conversion difference.

Tab. 1 Specific elastic storativity S_s (from MIRONENKO–SHESTAKOV, 1978

H Depth (m)	Rock	S_s (m^{-1})
10–50	sand clay	0.007/H $4 \times 10^{-4} - 7 \times 10^{-4}$
50–200	sand clay sandstone, siltstone limestone, marl	$5 \times 10^{-5} - 2 \times 10^{-4}$ $1 \times 10^{-4} - 4 \times 10^{-4}$ $3 \times 10^{-5} - 1 \times 10^{-4}$ $1 \times 10^{-4} - 4 \times 10^{-4}$
deep-seated aquifers		$10^{-5} - 10^{-6}$ ± 1–2 orders of magnitude

Tab. 2 The most frequent values of total, additional and skin difference at aquifer tests

	d min. max..	Md(d) min. max..	d_a min. max	Md(d) min. max.	d_s min. max.	Md(d_S) min. max..
hydrogeologic boreholes less than 100 m deep	-0.15 +0.30 (+0.60)	+0.10 +0.20	-0.20 +0.50	+0.10 +0.25	-0.25 +0.60	0.10
deeper hydrogeo-logic boreholes	-0.10 +0.80 (+1.00)	-0.20 +0.50	-0.20 +0.60	+0.10 +0.30		
small-diameter boreholes of mine-ral deposits explo-ration	-0.10 +1.10 (+1.20)	+0.30 +0.60	-0.10 +1.00	+0.30 +0.40	-0.10 +1.00	+0.30 +0.40

d = total conversion difference, d_a = additional difference, d_S = skin difference M_d = the most frequent median values in large sets of data possible more seldom values are given in parentheses

The hydraulic conductivity estimated from injection rate is often expressed as

$$k = C_f . g_h / L \qquad (50)$$

where C_f is a dimensionless constant (shape factor). Particular values of C_f were derived for various assumed patterns of flow about the test zone (HVORSLEV, 1951, LOUIS–MAINI, 1970, ZIEGLER, 1976, GALE et al., 1982, CHAPUIS, 1989 and others), but they yield very discrepant results. As follows from the analysis of the relations between injection rate and hydraulic conductivity, the shape factor C_f cannot be constant being actually a function of transmissivity and storativity (JETEL, 1993b). The conversion of injection rate to the parameter Z' implies the use of the conversion difference d for estimating hydraulic conductivity. The injection test conditions differ distinctly from both the steady-state flow described by Dupuit formula and the unsteady constant-discharge flow expressed by COOPER-IACOB approximation. As shown by DOE and REMER (1980), the constant-head radial flow model should be used to the analysis of unsteady flow at injection tests.

It is the choice o proper radius of influence r_d that is the key to the optimization of the conversion difference value for injection tests. With this in mind

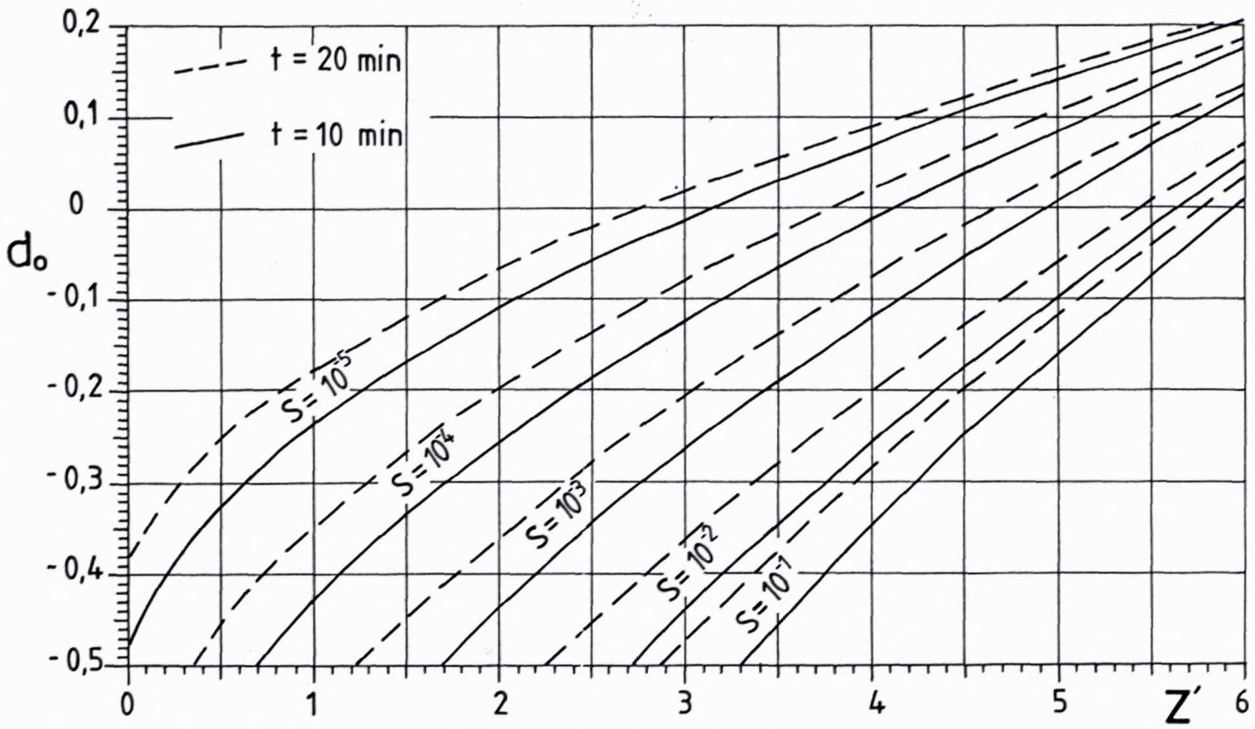

Fig. 1. The basic conversion difference d_o at water injection test as a function of permeability index Z', test time t and estimated storativity of tested interval S

we adopted the approach suggested by DOE and REMER (1980). The error in using steady- flow formula (Dupuit equation)

$$Q_s = 2\pi k s_h L / \ln(rd/rw \qquad (51)$$

(r_d = radius of influence, r_w = radius of ideal well free of well loss, L = length of tested interval) rather than the transient technique can be quantified by preparing flowrate data versus time plots using the equation of constant-head unsteady radial flow (JACOB–LOHMAN, 1952)

$$Q_t = 2\pi T s G(\chi) \qquad (52)$$

where G (χ) is the constant-head well function. When substituting s_h from Eq. (48) for the drawdown s, Q_t will be the injection rate in the time t. The average flowrate Q_{ta} over the period of time flowrate data were taken is determined by integrating the flow over the period of time in question. By comparing step-by-step the Q_{ta} values representing the average Q_t from Eq. (52) in the final pseudostabilized phase of the test with the Qs values from Eq. (51) at varying r_d/L and k, the optimum r_d/L value is found as the value yielding zero difference between Q_{ta} and Q_s.

The analysis made by DOE–REMER (1980) indicated the essence of relations between variables in question. It is however insufficient to a generally applicable determination of optimum values of r_d for estimating hydraulic conductivity. In particular variants the values L = 3 m, 2 r_w = 79 mm and s_h = 30 m were taken as constants corresponding to the most cases interpreted hitherto. More detailed information on the computations and their results is given by Jetel (1993b). Substituting the values of r_d for which $Q_s = Q_{ta}$ into Eq. (26), the optimum values of d_o were found as a function of the Z' and storativity of the tested interval. The results are shown in Fig. 1. The computed relations are described approximately also by the following regression equations:

– for the test time 10 min

$$d_o = 0.395\ Z^{1/2} - 0.130 \log S - 1.330 \qquad (53)$$

– for the test time 20 min

$$d_o\ 6= 0.348\ Z^{1/2} - 0.118 \log S - 1.155 \qquad (54)$$

The equations (53) and (54) predict fairly well the actual values of do at $S = 10^{-5} - 10^{-4}$ but they cannot be recommended for S exceeding 10^{-3} where they begin to fall off conspicuously from the directly determined values.

As to the choice of storativity values, in the uppermost parts of the near-surface zone close to the water level it is recommended to assume the values of the order of $S = 10^{-2}$, exceptionally 10^{-1}. In deeper parts the relation

$$S = S_s \cdot L \qquad (55)$$

can be used with the data from Tab. 1.

The comparison of the determined optimum values of r_d/L with the values of C_f suggested by the authors mentioned above shows that the constant C_f could be valid in very narrow ranges of S and k only.

The conversion of the values of Z' is applied mainly when converting the statistical characteristics of Z' values to the respective characteristics of hydraulic conductivity distribution e. g.- in particular depth zones. To adjust the determined value of do for additional resistances we recommend to add to the value of do from Fig. 1 as a conventionally accepted estimate $d_a = 0.05$ or, at high injected rates exceeding 10–20 liters per minute, $d_a = 0.10$.

Statistical evaluation of water injection data

After the conversion to the values of Z', the results of water injection tests are statistically evaluated in the same way as with aquifer tests. With regard to regular decrease of mean permeability with depth, the data sets are defined not only by regions and lithostratigraphic units but also according to chosen depth zones (JETEL, 1985 ac, 1994) and by the position in the relief (valley bottoms or slopes). It is extremely important to determine the parameters of exponential regression equation

$$k(H) = k_o \exp(-AH) \qquad (56)$$

where k(H) = mean hydraulic conductivity expected at the depth H, k_o = theoretical hydraulic conductivity for H = 0, A = exponential decrease coefficient. This type of equation presents an optimum approximation of the course of permeability changes with depth. Thus, the parameters k_o and A are the cardinal characteristics of hydraulic behaviour of rock massif at permeability decreasing with depth. However, in different depth zones these parameters can change (A usually decreases with depth).

Conclusions

When evaluating the archival data of aquifer tests or of water injection tests, the data on specified capacities and water injection rates can serve as invaluable information base. By means of conversion to the approximative logarithmic parameters Z and Y it is possible to arrive to consistent estimates of regional characteristics of permeability a transmissivity. The key to an optimum estimate of hydraulic coefficients corresponding to the approximative indices Z and Y is the determination of proper conversion difference d. The delineated procedure proved to be useful at regional hydrogeological research in many regions of various types. Its application is conditioned by sufficient number of data allowing to compute at least specific capacities (the ratio discharge (drawdown) or water injection rate. It is possible to include in the evaluated data – after appropriate logarithmic transformation - also the values of hydraulic conductivity or transmissivity determined directly by exact methods, namely by transient techniques (e. g. straight-line method).

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SLOVAK GEOLOGICAL MAGAZINE

Hydraulic Parameters of Sediments of the Inner Carpathian Paleogene in Eastern Slovakia

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Abstract:

In the presented paper the author evaluates hydraulic properties of the sediments of the Inner Carpathian Paleogene in a part of Eastern Slovakia. The sediments are divided into four lithostratigraphic units - the Borové, Huty, Zuberec and Biely Potok Formations. Their hydraulic properties are evaluated with the help of comparative parameters of transmissivity index - Y-, permeability index - Z -, from which the hydraulic parameters - transmissivity coefficient - T- and permeability coefficient -k- have been derived. The formations are classified according to the calculated -T- and -k- values in corresponding transmissivity and permeability classes. On the basis of general evaluation, the highest transmissivity, or permeability, showed the Borové Formation – tectonically affected homogeneous breccias and conglomerates formed of Triassic carbonate rocks, and the lowest by the Huty and Zuberec Formations (Tab. 1, 2, 3).

Key words: Inner Carpathian Paleogene, hydraulic parameters, transmissivity, permeability

(5 Figs., 3 Tabs.)

Introduction

Paleogene sediments form a considerable part of Slovakia. They emerge to the surface in the Eastern as well as Inner Carpathians. In the Inner Carpathians they are described as the Inner Carpathian Paleogene - the Subtatric Group. GROSS et al. (1984) distinguished here four Formations.

The base is formed of the Borové Formation, lying transgressively on the pre-Tertiary basement consisting mostly of Triassic limestones and dolomites. It consists of breccias, conglomerates, sandy limestones, passing towards the overlier into clayey limestones. Breccias and conglomerates are developed in two lithologic types. The first type consists of homogeneous breccias and conglomerates, the material of which comes from Triassic carbonates, and they are cemented with carbonaceous cement. The second type consists of heterogeneous breccias and conglomerates with polymictic material, formed mostly of non-carbonate rocks with clayey cement. Their age is estimated as Middle Eocene.

Above the Borové Formation is lying the Huty formation. It is formed of a thick and quite monotonous complex of calcareous claystones with sandstone beds. The ratio of sandstones vs. claystones is 1 : 4 to 1 : 10, sporadically even more. As far as its age is concerned, the formation belongs to the Upper Eocene.

The Zuberec Formation develops gradually from the Huty formation, the sandstone beds increasing and claystones decreasing in quantity, until it passes into a flysch development, with regularly alternating sandstones and claystones. According to its age it belongs to the middle part of the Upper Eocene.

The youngest formation of the Inner Carpathian Paleogene is the Biely Potok Formation, characterised by the development of heavy-bedded sandstones with sporadic non-calcareous claystone layers. The age of the formation is Lower Eocene.

Sediments of the Inner Carpathian Paleogene have been affected by germanotype tectonics. They are horizontal, or subhorizontal, only at the margin of basements the position is steeper.

The subject of the presented paper is regional evaluation of hydraulic properties of the subsurface zone of Inner Carpathian Paleogene sediments in Eastern Slovakia. The studied territory includes two regions – the Levočské vrchy Hills and Šarišská vrchovina Hills (Fig. 1), formed predominantly of the Biely Potok Formation. Other formations occur in their marginal parts (ZAKOVIČ, 1980 a,b)

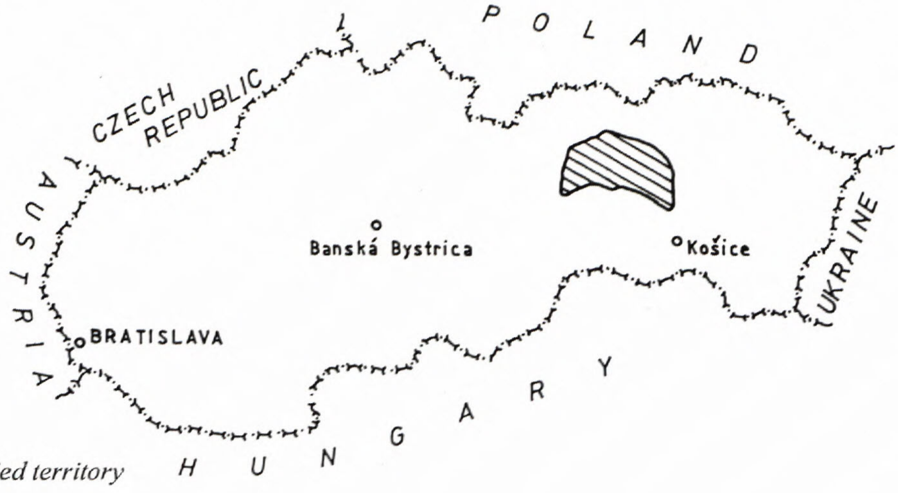


Fig. 1 Situation of the studied territory

Methods of data processing

The evaluation of hydraulic properties of sediments in the above lithostratigraphic units was based on the processing of comparative hydrogeologic parameters - the transmissivity index -Y-, permeability index -Z- - according to the method of regional evaluation of hydraulic rock parameters elaborated by JETEL (1985 a, b). The basic step was determining the transmissivity index -Y- and permeability index -Z- from values of specific yield -q-, derived from data provided by pumping hydrodynamic tests.

The values of hydraulic parameters – transmissivity coefficient -T- and hydraulic conductivity coefficient -k- are derived from the values of comparative parameters Y and Z with the help of logarithmic calculation difference -d- (JETEL, 1985 a) defined by the formula d = logT - logq, which, after its estimation or analytical derivation, is substituted into the calculation formulae (JETEL, 1985 a, b):

$$T\ (m^2/s) = \text{antilog}\ (Y + d - 9) = 10^{(Y + d - 9)} \qquad (1)$$

$$k\ (m/s) = \text{antilog}\ (Z + d - 9) = 10^{(Z + d - 9)} \qquad (2)$$

The degree of transmissivity and permeability in the studied lithostratigraphic units is expressed as medians Md(Y) and Md(Z) and arithmetic means M(Z) and M(Y). After substituting the estimations of calculation difference -d- into the formulae (1) and (2), we obtain respective estimations corresponding to the characteristics of middle level of transmissivity coefficient T and coefficient of hydraulic conductivity -k-, i.e. the medians Md(T) and Md(k) and the geometric means G(T) and G(k). As shown by the formulae (1) and (2), the comparative parameters Y and Z represent certain logarithmic transformations of the transmissivity coefficient -T- and permeability coefficient -k-. According to these relations, the arithmetic mean M of the values Y and Z corresponds to the geometric mean G of the values T and k:

$$G(T) = \text{antilog}\ M(Y + d - 9) = 10^{M(Y + d - 9)} \qquad (3)$$

$$G(k) = \text{antilog}\ M(Z + d - 9) = 10^{M(Z + d - 9)} \qquad (4)$$

Normal distribution of the values Y or Z indicates then lognormal distribution of the values -T- or -k- (JETEL, 1985 a,b).

As indicators of transmissivity and permeability variability in various lithostratigraphic units are used the values s_Y and s_Z, representing estimations of the standard deviation of the values Y and Z in the basic set.

The level of transmissivity is evaluated using the classification proposed by KRÁSNÝ (1986), for the level of permeability we use its eight-degree classification (JETEL, 1982).

Hydraulic parameters of lithostratigraphic units

Borové Formation

It is the lowermost lithostratigraphic unit of the Inner Carpathian Paleogene. Its hydraulic properties are characterised on the basis of data obtained from hydrogeologic drillholes. Trasmissivity and permeability of this formation is depending on its lithologic composition and tectonic reworking. Higher transmissivity and permeability classes are displayed by homogeneous breccias and conglomerates composed of Triassic limestone and dolomite pebbles, in contrast to heterogeneous conglomerates and breccias the pebble material of which consist besides Triassic carbonates of non-carbonate rocks, often cemented by clayey cement.

The characteristics of the distribution of transmissivity index Y, permeability index Z as well as estimations of transmissivity coefficients T and permeability coefficients -k- of the Borové Formation are presented in Tabs. 1, 2, 3, and Figs. 2, 3.

The transmissivity index in homogeneous conglomerates and breccias is lying in the range 4.7 - 6.8, about the median Md(Y) = 5.6 and arithmetic mean M(Y) = 5.7. The transmissivity coefficient T varies between 1.23×10^{-4} - 1.44×10^{-2} m^2/s, with a median of 8.51×10^{-4} m^2/s and geometric mean G(T) = 1.26×10^{-3} m^2/s.

According to the classfication of transmissivity, this formation is classed as a highly transmissive aquifer, with great variability of transmissivity (class II).

The values of permeability index in the Borové Formation vary in the range Z = 4.2 - 5.9, about the median Md(Z) = 5.1 and arithmetic mean M(Z) = 5.0. This range of Z values corresponds to estimates of coefficient of hydraulic conductivity G(k) = 2.51×10^{-4} m/s, the M(Z) value corresponds to an estimate of geometric mean of the coefficient of hydraulic conductivity G(k) = 2.51×10^{-4} m/s. According to permeability, homogeneous breccias and conglomerates are classified as permeability class III - relatively strongly permeable, with great variability of permeability (Zaković et al., 1993).

In contrast to this, the Borové Formation formed of heterogeneous breccias and conglomerates, or tectonically unaffected homogeneous conglomerates, displays one class lower transmissivity and permeability. For example, Jetel – Vranovská (1990) mentioned for the Borové Formation in the Hornádska Basin transmissivity coefficients in the range 1.1×10^{-5} - 9.0×10^{-3} m^2/s, about the median 3.7×10^{-4} m^2/s and permeability coefficient in the range 1.2×10^{-7} - 3×10^{-4} m/s, with the geometric mean 9.5×10^{-6} m/s. This corresponds to the transmissivity class four (medium transmissivity).

Flysch formation

Above the Borové Formation there are flysch sediments – the Huty, Zuberec and Biely Potok Formations.

Groundwater forms in flysch sediments either by infiltration of precipitation, or by surface water penetrating into the rock environment. The principal hydrogeologic aquifer is the near-surface zone. The predominant part of the infiltrated precipitation water is flowing off more or less conformably with the surface terrain, in small depth below the surface. On more steep slopes, the near-surface zone, especially in its most permeable section, after interrupted influx of precipitation, it is very rapidly drained off and the table of the first groundwater body descends into less permeable parts of the rock environment. The movement of water table in the near-surface zone, with permeability and transmissivity decreasing with depth, is the reason for considerable variability of drainage from the territory. The greatest part of the groundwater flowing off in the near-surface zone passes into surface drainage by the way of disseminated transition into Quarternary alluvia and surface streams, and only a small part reaches the surface in the form of springs. Average yield of springs flowing off the flysch sediments is relatively low. Relatively abundant are springs with Q up to 0.51 l/s. An exception are springs at tectonic zones fed from the above- or underlying lithostratigraphic members, or springs occurring in the closure of valleys filled with a thicker cover of debris.

A smaller part of groundwater descends into greater depth in the direction of inclination of aquifer rocks as well as along vertical fault zones and it participates in the formation of springs flowing off on these faults or reached by hydrogeologic drilling.

Huty Formation

It is formed by grey, dark-grey claystones with varying calcareousness, with layers of sandstones. Its hydraulic properties are characterized on the basis of results obtained from hydrogeologic drill-holes.

The characteristics of the distribution of transmissivity index -Y-, permeability index values -Z-, transmissivity coefficients T and permeability coefficients -k- are presented in Tabs. 1, 2, 3 and on Figs. 2, 3. The transmissivity of the Huty Formation is characterised by the range of transmissivity index values Y = 4.3 - 5.2 with Md(Y) = 4.7, M(Y) = 4.7 and standard deviation $s_Y = 0.50$. This corresponds to estimates of the range of transmissivity coefficients T = 3.3×10^{-5} m^2/s and G(T) = 7.5×10^{-5} m^2/s.

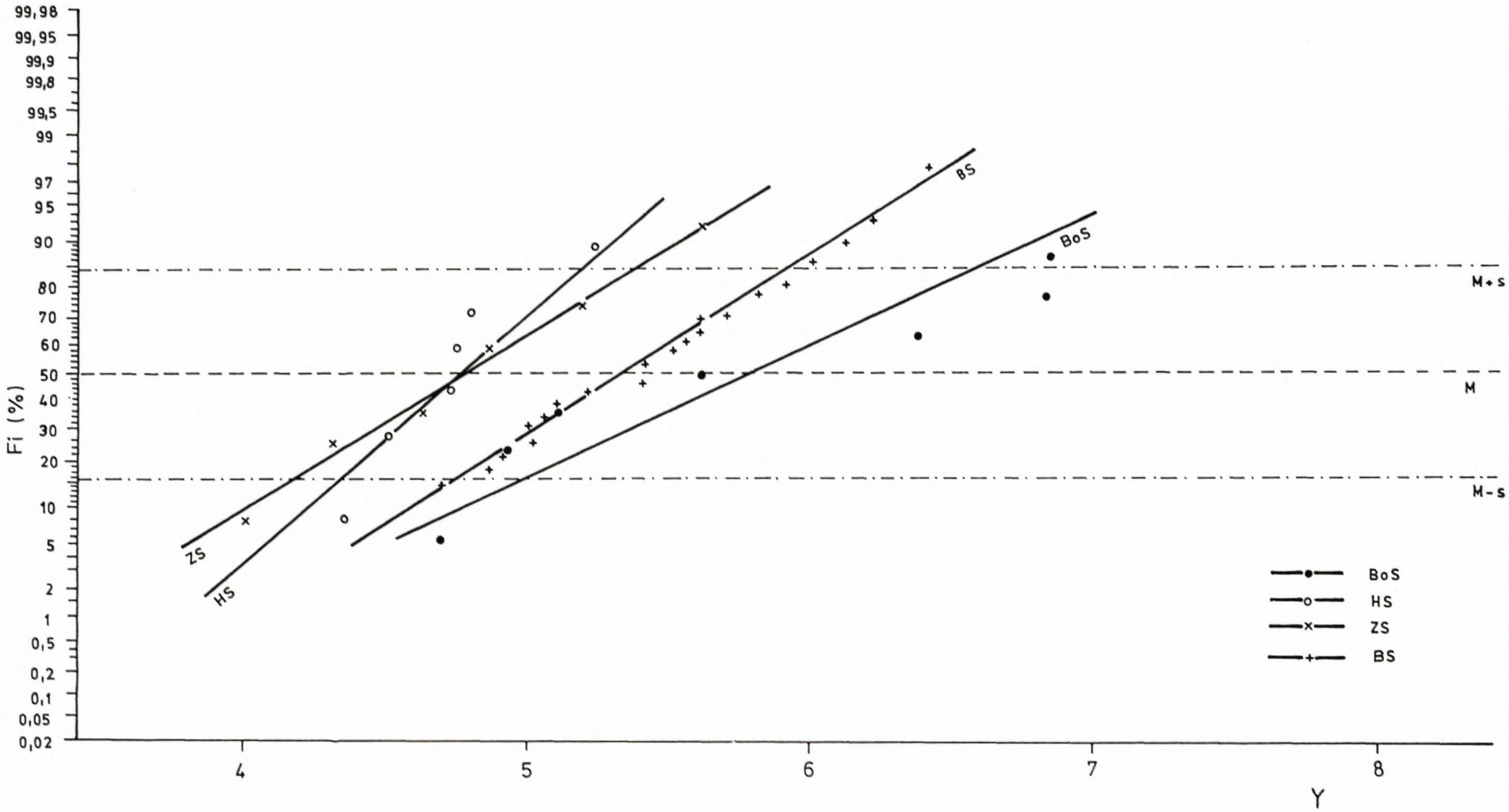


Fig. 2: Quantile graph of the transmissivity index (Y) for the studied lithostratigraphic units
BoS – Borové Formation, HS – Huty Formation, ZS – Zuberec Formation, BS – Biely Potok Formation.
On the vertical axis there are relative cumulative frequencies, M = arithmetic mean, s = estimate of standard deviation of the basic set

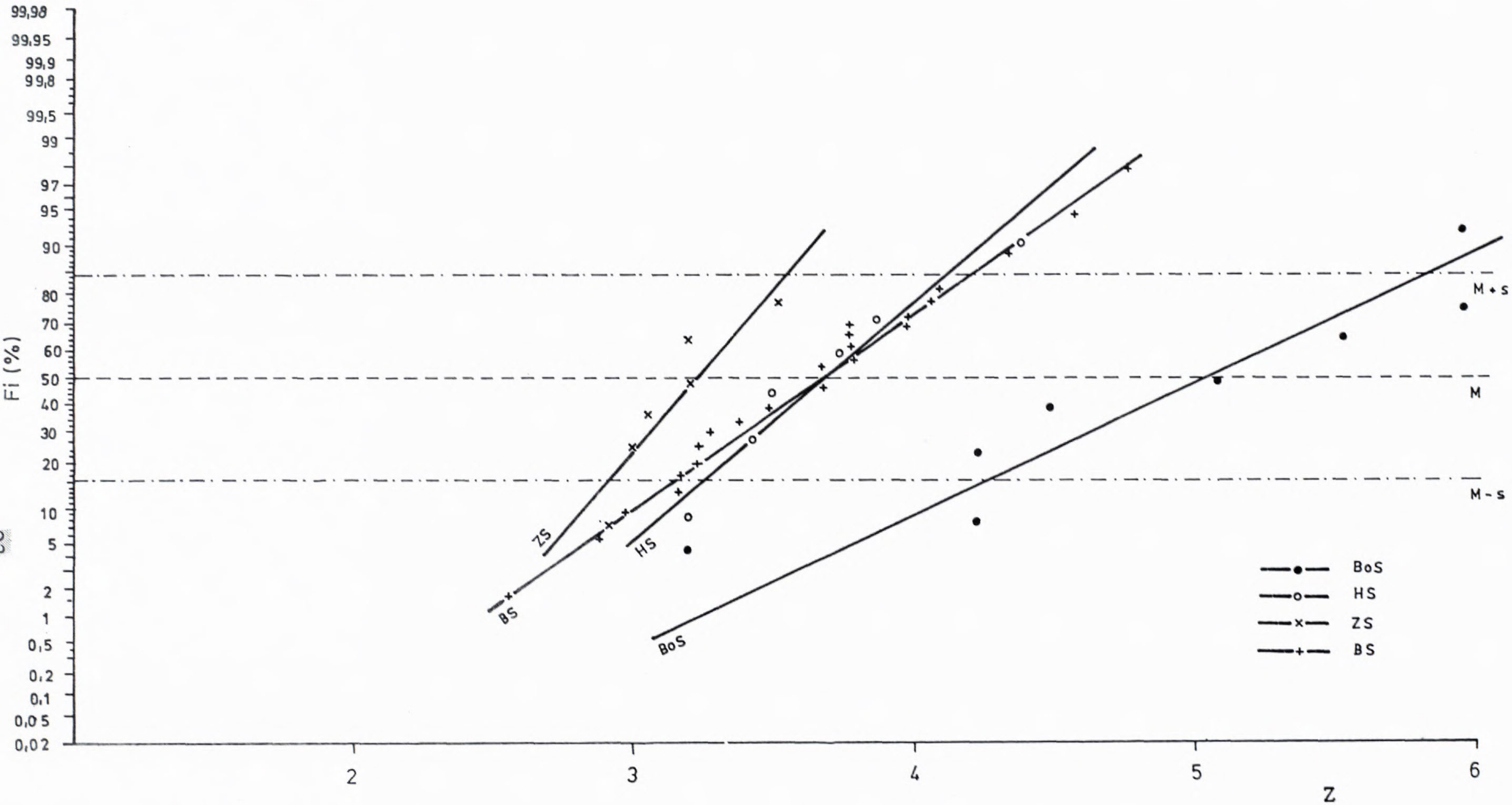


Fig. 3 : Quantile graph of the permeability index (Z) for the studied lithostratigraphic units. Explanations – see Fig. 2

Tab.1 Characteristics of the distribution of transmissivity index Y and permeability index Z values in the studied lithostratigraphic units

Lithostratigraphic unit	n	Y	Md(Y)	M(Y)	s_Y	Z	Md(Z)	M(Z)	s_Z
Biely Potok Formation	25	3,9–6,4	5,4	5,3	0,54	2,6–4,8	3,7	3,6	0,55
Zuberec Formation	7	4,0–5,6	4,7	4,7	0,62	1,5–5,4	3,7	3,7	0,84
Huty Formation	6	4,3–5,2	4,7	4,7	0,50	3,2–4,3	3,5	3,6	0,44
Borové Formation	7	4,7–6,8	5,6	5,7	0,80	4,2–5,9	5,1	5,0	0,78

n = number of data, Md(Y), Md(Z) = medians of the values Y and Z, M(Y) and M(Z) = arithmetic means of the values Z and Y, s_Y, s_Z = standard deviation estimates of the basic set for the values Y and Z

Tab. 2 Distribution of estimates of transmissivity coefficient T derived from transmissivity index Y

Formation	n	R(T)(m^2/s)	G(T)	Transmissivity class
Biely Potok Formation	25	$1,5.10^{-5}$– $4,4.10^{-3}$	$3,8.10^{-4}$	III. Medium Transmissivity
Zuberec Formation	7	$1,4.10^{-5}$–$5,7.10^{-4}$	$8,3.10^{-5}$	IV. Low Transmissivity
Huty Formation	6	$3,3.10^{-5}$–$2,4.10^{-2}$	$7,5.10^{-5}$	IV. Low Transmissivity
Borové Formation	7	$1,2.10^{-4}$–$1,4.10^{-2}$	$1,2.10^{-3}$	III. High Transmissivity

n = number of data, R(T) = range of transmissivity coefficient values, G(T) = geometric mean of transmissivity coefficient

Tab. 3 Distribution of hydraulic conductivity coefficient estimates derived from permeability index Z

Formation	n	R(k)	G(k)	Permeability class
Biely Potok Formation	25	$7,6.10^{-7}$–$1,2.10^{-4}$	$1,7.10^{-5}$	IV. medium
Zuberec Formation	7	$1,1.10^{-6}$–$9,1.10^{-6}$	$3,2.10^{-6}$	V. relatively low
Huty Formation	6	$2,2.10^{-6}$–$1,9.10^{-3}$	$7,0.10^{-6}$	V. relatively low
Borové Formation	7	$3,5.10^{-5}$–$1,9.10^{-3}$	$2,5.10^{-4}$	III. relatively high

n = number of data, R(k) = range of coefficient of hydraulic conductivity values, G(k) = geometric mean of coefficient of hydraulic conductivity

The values of permeability index vary here in the range Z = 3.2 - 4.3, about the median Md(Z) = 3.5 and arithmetic mean 3.6, with an estimate of standard deviation of the basic set s_Z = 0.44. This range of Z values corresponds to estimates of the coefficient of hydraulic conductivity k = $2.26x10^{-6}$ - $3.5x10^{-5}$ m/s, the value of M(Z) corresponds to the estimate of geometric mean of coefficient of hydraulic conductivity G(k) = $7.0x10^{-6}$ m/s.

According to the eight-degree permeability classification of JETEL (1982), average permeability of the near-surface zone in the Huty Formation corresponds to class V (relatively weak permeability and transmissivity) – IV (low transmissivity).

Zuberec Formation

The Zuberec Formation consists of grey, weakly calcareous claystones and clayey siltstones, with layers of gradation-bedded sandstones, which sometimes reach a thickness of 2 or more meters.

Hydraulic parameters of the Zuberec Formation are evaluated on the basis of 7 data obtained from hydrogeologic drillholes. The transmissivity index is in the range Y = 4.0 - 5.6, with a median of Md(Y) = 4.79, arithmetic mean M(Y) = 4.76, at standard deviation s_Y = 0.62. This corresponds to estimates of transmissivity coefficient T = $1.45x10^{-4}$ m^2/s and G(T) = $8.32x10^{-5}$ m^2/s. According to these values, the Zuberec Formation is characterised as aquifer with low transmissivity (class IV).

Values of permeability in the near-surface zone of the Zuberec Formation vary in the range Z = 2.9 - 3.8, Md(Z) = 3.2 and M(Z) = 3.25 at standard deviation of 0.31. This range of Z values corresponds to estimates of coefficient of hydraulic conductivity k = $1.14x10^{-6}$ m/s and G(k) = $2.57x10^{-6}$ m/s. The near-surface zone of the Zuberec Formation is thus according to average permeability classified as relatively weakly permeable aquifer with low variability of permeability (permeability class V).

Biely Potok Formation

The youngest formation of the Inner Carpathian Paleogene is the Biely Potok Formation. It is formed predominantly of sandstones, with minor occurrences of claystones and microconglomerates. In the studied territory it attains the greatest areal extent.

Hydraulic properties of this formation may be characterised on the basis of 25 data obtained from hydrogeologic drillholes. The characteristics of the distribution of transmissivity, permeability index and transmissivity and permeability coefficient values are presented in Tabs. 1, 2, 3 and on Figs. 2, 3 (ZAKOVIČ et al., 1993)

The transmissivity index of the Biely Potok Formation has a range of 3.9 - 6.4, Md(Y) = 5.4, M(Y) = 5.3 at standard deviation of 0.54. The transmissivity coefficient may be estimated from the above values - T = $1.52x10^{-5}$ - $4.48x10^{-3}$ m^2/s, G(T) = $3.82x10^{-4}$. According to transmissivity values, the Biely Potok Formation may be classified as medium transmissivity aquifer (transmissivity class III).

The permeability of the studied sections of the Biely Potok Formation is characterised by values of permeability index -Z- (Tab. 1). The Biely Potok Formation has a permeability index of Z = 2.6 - 4.8, Md(Z) = 3.7, M(Z) - 3.6 and standard deviation s_Z = 0.55. These values correspond to estimates of k = $7.6x10^{-7}$ - $1.2x10^{-4}$, G(k) = $1.74x10^{-5}$. The near-surface zone of the Biely Potok Formation is classified according to average permeability as medium-permeable aquifer ranked with permeability class IV.

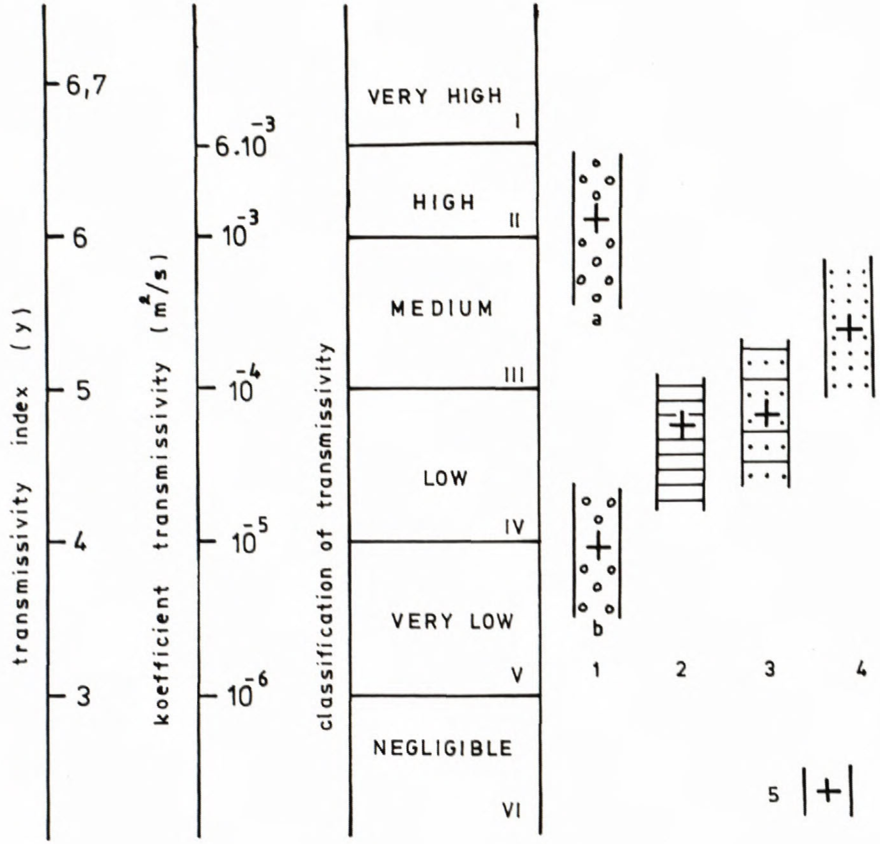
Summary comparison of transmissivity and permeability of lithostratigraphic members of the Inner Carpathian Paleogene

As indicated by Tabs. 1–3, Figs 2–3, providing an overview of the characteristics determined in the near-surface zone of the studied members, average permeabilities and transmissivities determined for these members on the basis of pumping tests differ relatively little from each other. The highest transmissivity is displayed by the Borové Formation - tectonically affected homogeneous breccias and conglomerates consisting of Triassic limestone and dolomite pebbles. They belong to class II – high transmissivity (Fig. 4).

The Biely Potok Formation belongs into transmissivity class three - medium transmissivity (T = $1x10^{-4}$ - $1x10^{-3}$ m^2/s).

The Huty and Zuberec Formations belong into transmissivity class four – low transmissivity (T = $1x10^{-5}$ - $1x10^{-4}$ m^2/s).

The Borové Formation, formed of heterogeneous breccias and conglomerates, is on the bound-



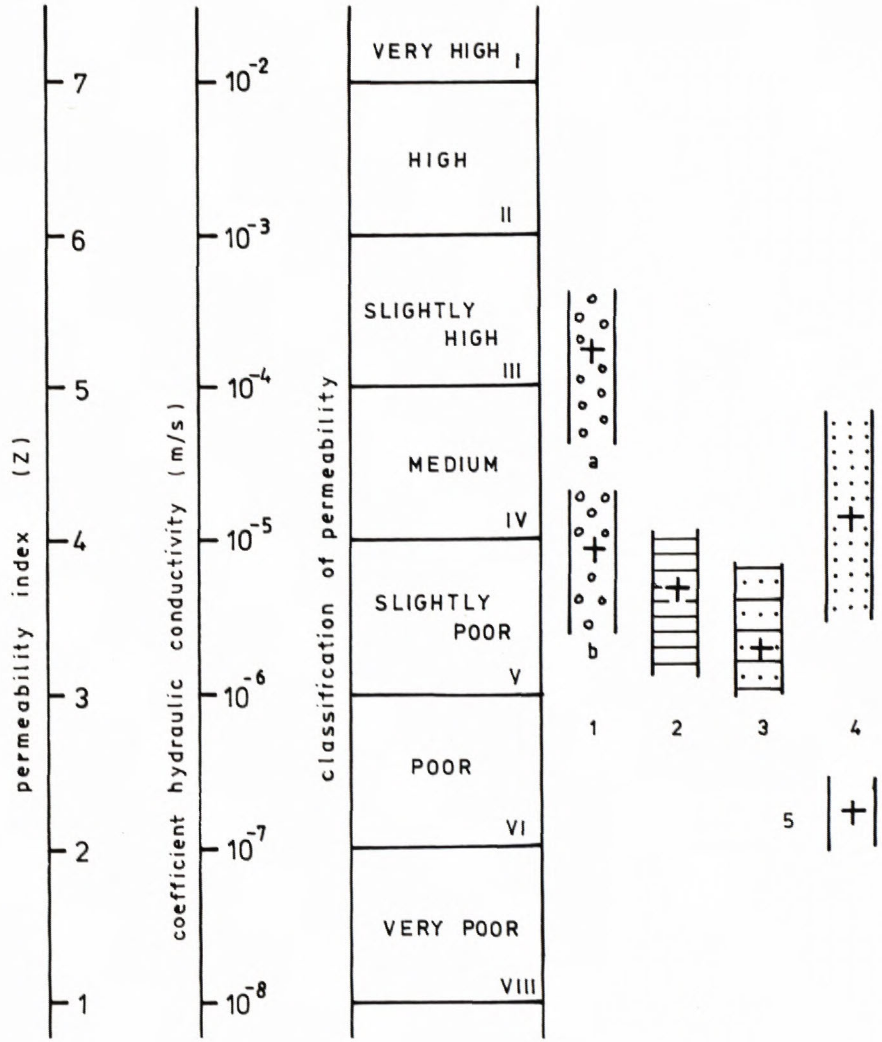


Fig. 4 : Comparison of the characteristics of transmissivity for the studied lithostratigraphic units
1 – Borové Formation: a) homogeneous conglomerates and breccias, tectonically affected, b) heterogeneous conglomerates and breccias, 2 — Huty Formation, 3 – Zuberec
Formation, 4 – Biely Potok Formation, 5 – average value of the transmissivity coefficient

Fig. 5: Comparison of the characteristics of permeability for the studied lithostratigraphic units. Explanations - see Fig. 4.

ary of classes four and five (low to very low transmissivity).

Similarly we can characterise the lithostratigraphic units according to permeability (Fig.5). The highest average permeability is displayed by the tectonically affected Borové Formation. It is classified in the permeability class three - relatively strong.

The Biely Potok Formation belongs into the permeability class four – medium permeability (k = 1×10^{-5} - 1×10^{-6} m/s).

The Borové Formation formed of heterogeneous breccias and conglomerates is lying on the boundary of classes four and five.

The Huty and Zuberec Formations belong into the permeability class five - relatively weak (k = 1×10^{-6} - 1×10^{-5} m/s).

Conclusion

When applying the determined characteristics of transmissivity and permeability of Inner Carpathian Paleogene lithostratigraphic units to practice, we must take into consideration the fact that due to spatial non-uniformity of the near-surface zone, these characteristics correspond to near-surface zone in depressions of the territory - valleys and lower parts of slopes. The majority of hydrogeologic drillholes, which provided data for determining the hydraulic parameters, is situated predominantly in valleys, and thus they yield information above all on transmissivity values of the valleys. Jetel (1990) pointed out that in the majority of terrains formed of flysch sediments, four quantitatively different transmissivity categories must be distinguished, relative to the position of the studied part of the territory in the relief of the surface, i.e. transmissivity of the near-surface zone in the bottom of valley and at foot of hills, slope transmissivity of the near-surface zone in slopes, transmissivity of deeper parts of the rock massif (except fissure zones) and transmissivity of fissure zones (tectonically affected zones), the differences between the transmissivity of these categories may reach even several orders in the same environment. Therefore it is necessary to bear in mind that the near-surface zone in slopes will have lower average transmissivity than above presented results from hydrogeologic drillholes.

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SLOVAK GEOLOGICAL MAGAZINE

Influence of Land Use on Water Quality in Mountainous Areas – A case study from Slovakia

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Abstract:

Geologic and geomorphologic conditions of Slovakia are very complicated, which is reflected also in the complex hydrogeologic conditions of the territory. Several surveys of regional character studied in detail all factors controlling groundwater quantity and quality on the territory of Slovakia. However, the authors only rarely studied the effects of land use character (type) on groundwater quality.

Key words: natural water, contamination, land use, technogenic condition

(8 Figs., 5 Tabs.)

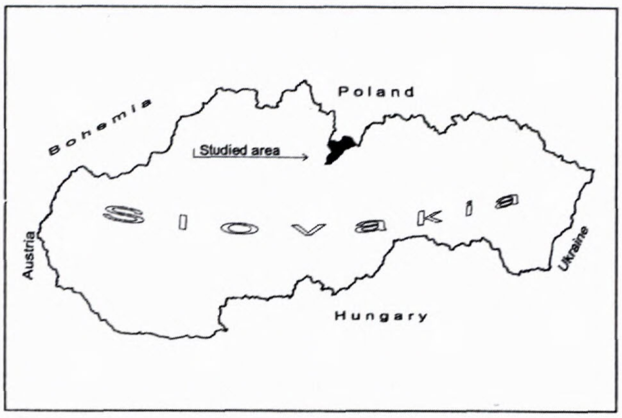

Fig. 1: Localisation of the studied area

Introduction

Geologic and geomorphologic conditions of Slovakia are complicated, which is reflected also in the complex hydrogeologic conditions of the territory. In several surveys of regional character (GAZDA, 1983, HANZEL et al., 1984, HANZEL et al., 1989) all factors controlling groundwater quantity and quality have been studied in detail. However, the authors studied only rarely in detail the effects of land use character (type) on groundwater quality.

The territory of Slovakia may be divided from the viewpoint of relief type and economic exploitation into several units (MAZÚR, 1980):

- Areas of lowlands and open basins – relief with very high potential for economic activities
- Areas of closed basins and flat furrows – relief with high potential for economic activities
- Areas of foothills, low platforms and closed furrows – relief with limited potential for economic activities
- Areas of disjointed uplands and platforms – relief with low potential for economic activities
- Areas of massive uplands, mountains and high mountain ranges – relief with very low potential for economic activities

The presented contribution is focused on the analysis of the relationship between water quality and type of land use on the example of the river Belá, Tatry Mts., Slovakia.

The upper part of the Belá catchment is found in the Vysoké and Západné Tatry Mts., representing the mountainous part of the Slovak territory, and the lower part is located in the Liptov Basin, representing the foothills (Fig.2). From the viewpoint of land use they are two different units (two land structures), with different potential of use.

The lower part of the catchment (Liptov Basin) is a high-lying basin accumulation-erosion land. The upper part (Tatry Mts.) is a mountainous land with higher altitude levels.

The Liptov Basin represents the type of a multifunctional, industrial-recreational-agricultural land with three subtypes. One of them are areas of urban industrialised land, with predominant technical-constructional elements (industry, communications etc.). Another subtype is agricultural land of rural to

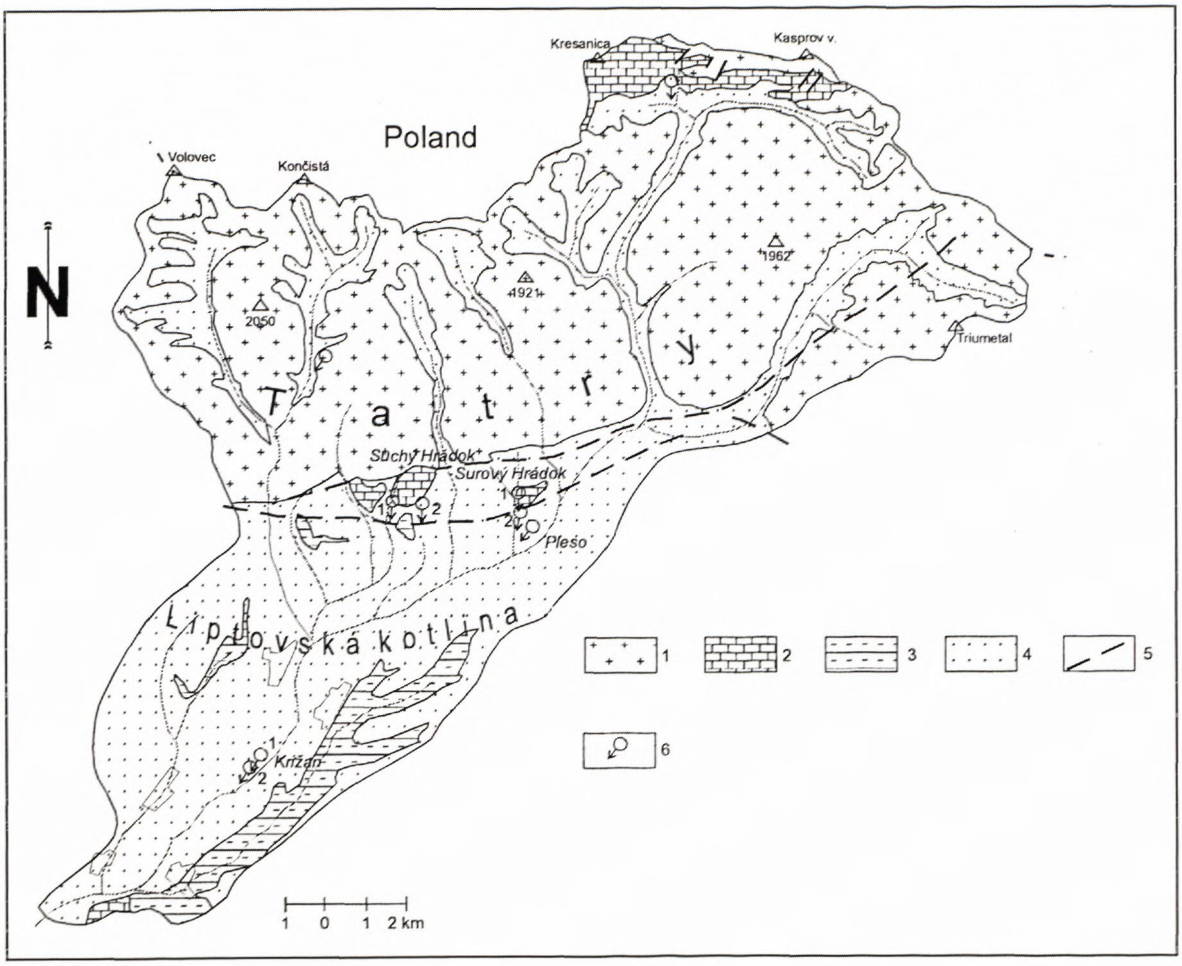

Fig. 2: Hydrogeologic sketch of the Belá river catchment

1 – granitoids, crystalline schists, fracture permeability, 2 – limestones, dolomites, quartzites, Mesozoic as a whole, fracture and karst-fracture permeability, 3 – alternation of sandstones and claystones, Paleogene, as a whole unpermeable, 4 – gravel-sand and boulder sediments, Quartenary, intergranular permeability, 5 – faults, subtatric fault zone, 6 – important springs

transitional-rural settlement structure, with arable land - grassy cultures, which is the greater part of the basin. Only on the northern margin of the basin there is agricultural-recreational to recreational land with predominant grassy-forest cultures and recreation facilities. The last two subtypes are characteristic of the lower part of the studied catchment. From the viewpoint of raw material the potential of the Liptov Basin is connected only with occurrences of construction materials (gravels, building stone).

The economic potential of the upper part of the catchment (in Tatry Mts.) is limited by the topography and altitude, reflected in the low population density and low degree of agricultural land use. This part of the territory has great tourism and recreation potential, manifested in the construction of various tourist facilities, sports facilities (ski lifts), building of tourist paths and roads. In this way the visitors rate of the territory increases extremely. In spite of this, Vysoké and Západné Tatry Mts. is a land type with little damaged structure.

The upper part of the catchment belongs to the Tatry National Park (TANAP), which should ensure land protection, connected with limited forest exploitation and protection of raw material resources.

Hydrology and hydrogeology

The Belá river catchment has a surface of 244.3 sqkm. With its altitude it belongs to the highest-lying catchments of Slovakia, the average altitude being 1283 m a.s.l. From the viewpoint of altitude range, the S part of the catchment (Liptov Basin) has the character of uplands (up to 300 m) and the N part (Západné Tatry and Vysoké Tatry Mts.) are high mountains (above 640 m) with typical glacial relief and glacially remodelled valleys (Tab.1).

According to the Atlas of Slovak Socialist Republic (1980), the runoff regime in the Tatry Mts. (upper part of catchment) is transitional mountainous nival, in their lower parts nival-pluvial, and in the lower part (Liptov Basin) nival-pluvial. The higher is the relief, the more rapid is the water runoff toward erosion bases and the shorter is the contact with rock environment.

Precipitation is the only source of water supply in the catchment. No surface water flows into the catchment, nor any surface water flows off. Similarly, groundwater does not flow in, but outflow of groundwater cannot be excluded. Water discharge in the Belá river catchment in the years 1984–1990 is listed in Tab. 2.

The conditions of groundwater source formation are considerably different in the upper and in the lower part of the catchment. A natural boundary (separating line) is the subtatric fault (Fig. 2).

The upper part of the catchment has a surface of 155.9 sqkm and is built predominantly of granitoids, partly crystalline schists (Fig. 2), with a surface of 148.5 sqkm, and in the highest-lying part of the catchment also by Mesozoic rocks of the Červené vrchy Mts., with a surface of 7.4 sqkm. The inhomogeneous crystalline massif of the Tatry Mts. is characterised by the presence of various local groundwater circulation ways and intensive infiltration of atmospheric precipitation, which is in fact the only source of water supply to groundwater resources. Important is however the hydrogeologic function of glacigenic sediments in valleys and at foot of slopes, the water of which is almost in all cases directly hydraulically connected with streams at the bottom of valleys. The groundwater regime of the crystalline massif in the upper part of the catchment is affected by the hydrogeologic structure of the Červené vrchy Mts. Mesozoic, built of

Tab.1 Characteristics of the studied catchment

Part of catchment	Mountain range Vysoké and ZápadnéTatry Mts.	Foothills Liptov Basin
Drainage area [sqkm]	155,9	88,4
Altitude [m a.s.l.]	900–2428 to	630–900
Length of river km	16,5	19,2
Inclination of drainage area %	14–30	0–6
Energy of relief [r = 1 km]	180-640 m and above extremely cut relief in part deeply to very deeply	30–180 m slightly hummocky to slightly cut relief
Climatogeographical type	mountain climate, cool to very cold	basin climate, cool
Temperature	January: -6 to -10° C July: 4 to 14°C	January: -5 to -6°C July: 14 to 17°C
Snow cover	180-250 days	120–180 days
Maximum snow cover	75–150 cm	25–75 cm
Annual precipitation	800 up to over 2000	700–800
Soil type	humus-ferriferrous podsols and primitive litosols	fluvial plane illmenised soils
Average annual elementary runoff [$l.s^{-1}$. sqkm]	20 to 60	10 to 20
Type of runoff regime	transitional nival, in lower parts also nival-pluvial	nival-pluvial

Data according to Atlas of Slovak Socialist Republic, 1980

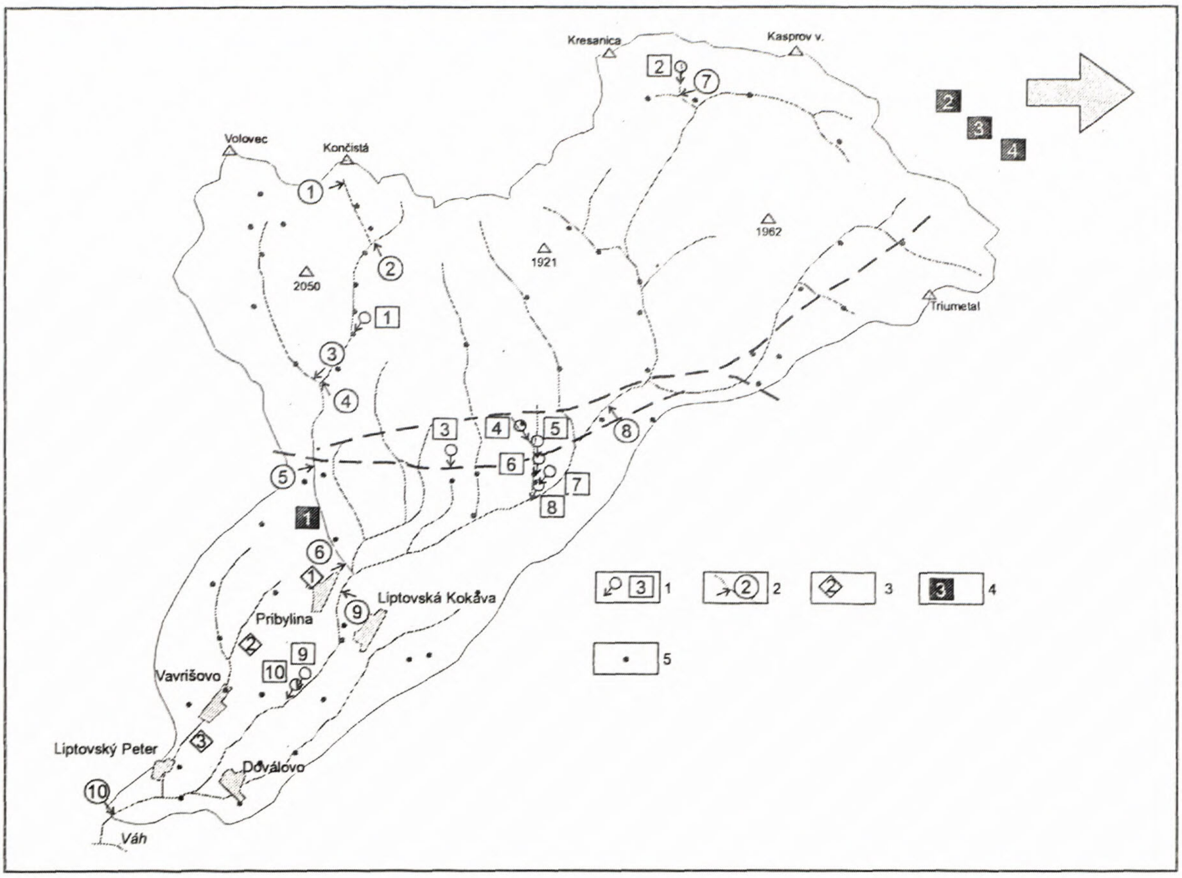

Fig.3: Localisation of sampling sites of water for chemical analysis in the Belá river catchment1
1 – spring , 2 – surface stream, 3 – borehole, 4 – snow, 5 – hydrochemical material (groundwater chemistry) from the project of VRANA *(1992)*

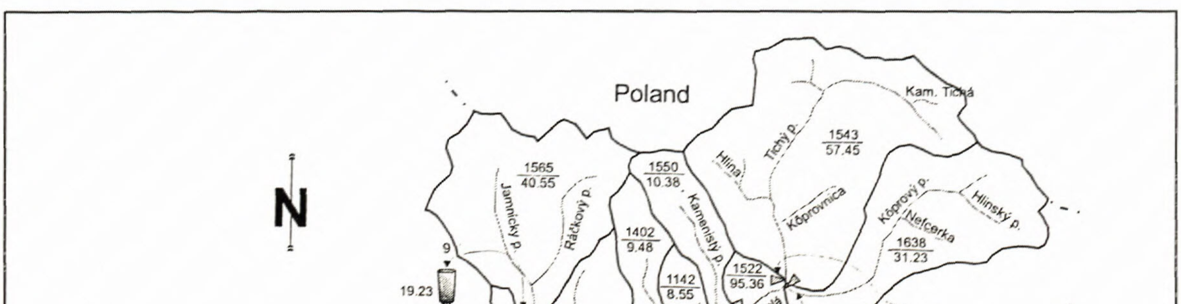

Fig.4: Specific groundwater runoff (l.s. sqkm) in the Belá river catchment (after MATUŠKA *et al., 1980)*

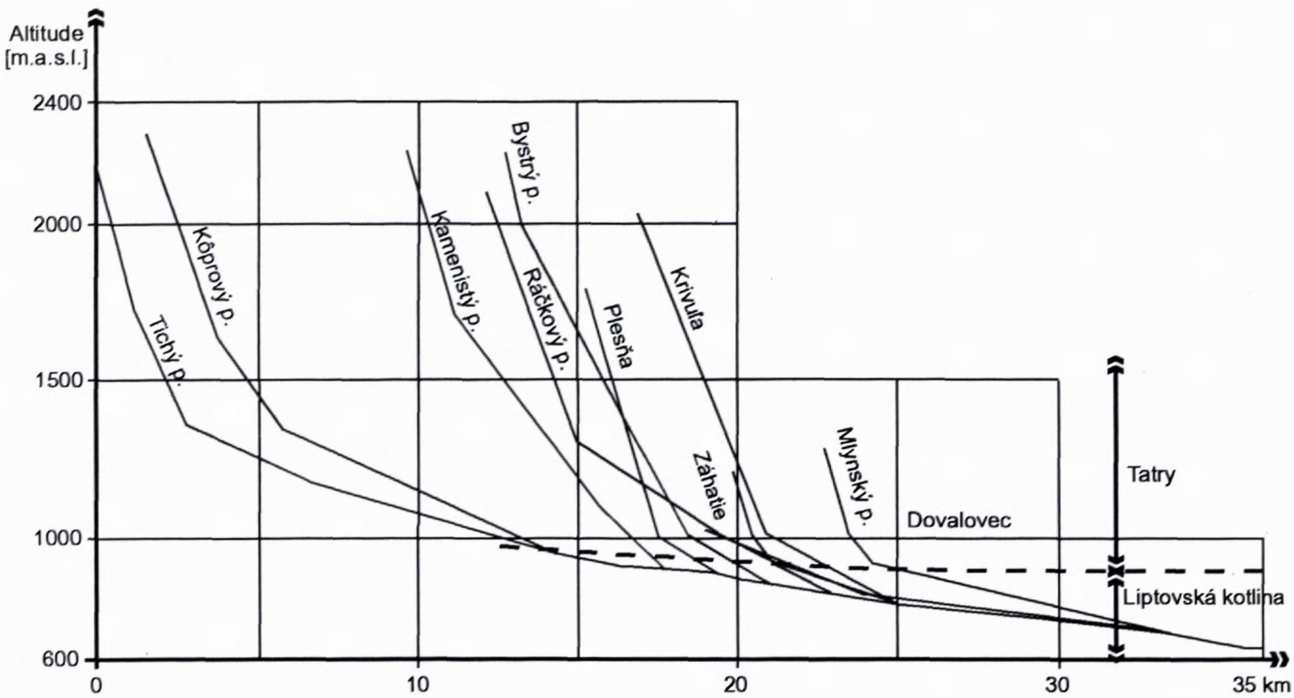

Fig. 5: Schematic lengthwise profile of river network in the Belá river catchment

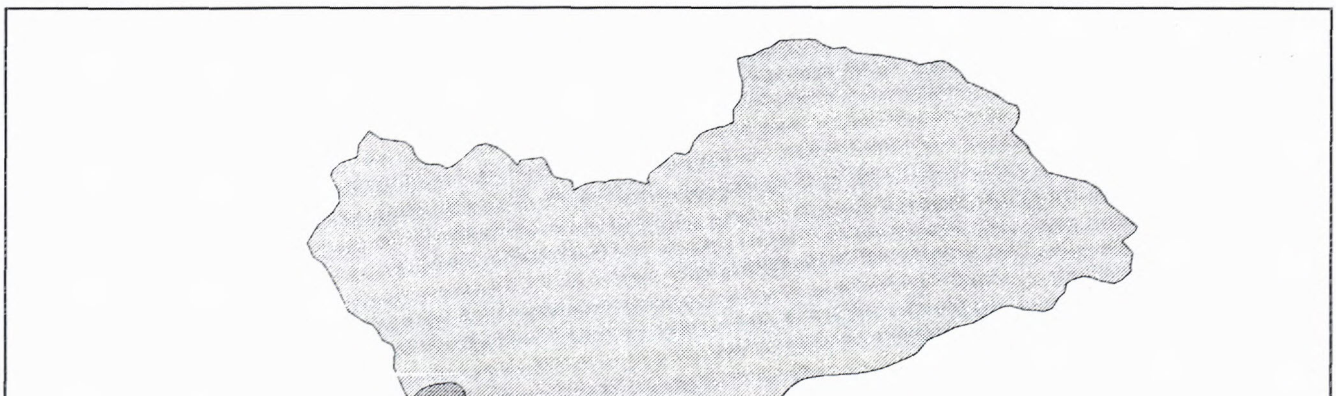

Fig. 6: Distribution of T.D.S. values (mg.l^{-1}) in groundwater. 1: <200; 2: 200-400; 3:400-600; 4: >600

strongly karsted Middle Triassic limestones. Three springs on the Slovak side of the Tatry Mts. have capacities of 18.5 to 60.0 l/s^{-1}. The substantial part of the carbonate structure is however drained into the Dunajec catchment on the Polish side of the Tatry Mts. Groundwater discharge from the Belá catchment is shown on Fig. 4. A lengthwise profile of the Belá catchment river network is presented on Fig. 5.

The crystalline massif has a great influence on the groundwater regime and circulation also in the lower part of the catchment, since along the subtatric fault it is neighbouring the Mesozoic, Paleogene and Quaternary sediments of the Liptov Basin (Fig.2). Due to its exposure and high precipitation, the Tatry Mts. crystalline massif is to a considerable extent the direct or indirect source of water supply to groundwater of younger sedimentary complexes. In spite of the fact that only small carbonate areas appear on the surface in the "islands" of Surový and Suchý Hrádok (with a surface of 0.25 and 1.17 sqkm, respectively), springs with very high capacities (average capacities 1 to 28 $l.s^{-1}$, see springs Suchý Hrádok 1, 2 and Surový Hrádok 1, 2 /No. 3, 4, 5, 6 on Fig. 3) are flowing out from these Mesozoic "islands". The springs are flowing out on the contact with impermeable Paleogene flysch sediments. High capacities of these springs are the result of extensive drainage effect of highly permeable carbonates and the subtatric fault, which are also draining groundwater from the adjoining crystalline massif and Quaternary sediments (HANZEL et al., 1990).

The lower part of the catchment in the Liptov Basin has a surface of 88.37 sqkm and it is built predominantly of Quaternary sediments, the underlier of which as a whole is formed of a relatively impermeable Paleogene flysch formation. Glacifluvial and fluvial Quarternary sediments (presenting the most favourable conditions for groundwater accumulation) are filling the fluvial plain of Belá from Podbanské to the confluence with Váh river, and they occur as well in the form of terraces. Hydraulic parameters of these sediments are documented in Tab. 3. Groundwater flow direction in Quaternary sediments is consistent with the inclination of the impermeable flysch underlier. The Belá fluvial plain becomes narrower in the direction of river flow, from about 2.0 km at Vavrišov to several tens of meters at Liptovský Peter (Fig. 2). As a result of this, groundwater cannot flow uninhibited in the fluvial sediments and a part is flowing out as springs.

Discharges of the significant springs from Quatenary sediments are in Tab. 4.

The river Belá drains its fluvial sediments all year long, only at high water levels in the river infiltration from the river into fluvial sediments may occur (however only in the area NE of Pribylina). Supply of water to Quaternary groundwaters in the lower part of the Belá catchment is mostly from snowmelt and by influx of groundwater from the higher situated cone of Račkova Valley (TUŽINSKÝ et al., 1971).

Groundwater of Quaternary sediments in the lower part of the catchment is supplemented by infiltration from precipitation, especially in the hilly part of the catchment, by infiltration from surface streams and, as documented by hydrometric work in the years 1985, 1988 and 1989, also by penetration of groundwater from the adjoining part of the Tatry Mts., from the entry of the Račkova Valley to Podbanské, where losses of water from surface streams have been recorded.

The mentioned natural and technogenic conditions affect in a decisive way the chemical composition of water on the territory.

Water chemistry

Chemical composition of natural water (snowmelts, streams, springs, boreholes) is listed in Tab. 5. These data are complemented for further graphical evaluation by chemical analyses of water from springs and boreholes obtained from the project "Geochemical Atlas of Slovakia" (VRANA, 1992). Their localisation is shown on Fig. 3. The presented snow chemistry allows to estimate initial chemistry of infiltrating water in the catchment.

Figs. 6, 7 and 8 show the distribution of total mineralisation, sulphate and nitrate values in the Belá river catchment. The distributions have been calculated using the inverse distance method and thus obtained data were subsequently smoothened by moving average method.

Discussion and conclusion

The presented hydrochemical data show that natural conditions in the Belá catchment are the reason for the differentiation of water chemistry, due to different hydrogeologic and hydrogeochemical properties of silicate and carbonate rocks. Springs in Mesozoic carbonates flowing out even in great altitudes (e.g. No. 2) have 2 to 3 times higher

Tab.2 Average monthly and annual discharge in the Belá river catchment in the years 1984-1990 (according to SHMÚ)

Flow station	surface (sqkm)	XI	XII	I	II	III	IV	V	VI	VII	VIII	IX	X	Ann. average
1. Tichý brook Tichá Val.	57,45	776	691	620	559	614	2301	5972	3704	2158	1751	2139	1139	1874
2. Kôprový brook Kôprová Val.	31,23	473	381	357	297	264	867	3136	2327	1328	1072	1228	790	1152
4. Kamenistý brook Podbanské	10,38	122	126	93	95	119	437	1282	717	279	210	310	200	334
9. Račkov brook Račková Val.	40,55	797	734	561	463	689	2187	4990	2528	1507	1219	1726	1134	1550
3. Belá Podbanské	95,36	1350	1155	1068	919	957	3629	10683	5472	3895	2985	3723	2184	3263
11. Belá Lipt. Hrádok	244,30	2789	2566	2039	1862	2587	7645	19089	11209	6624	5042	6605	4231	6038

Tab. 3 Hydraulic parameters from Quaternary sediments of Belá

Profile	Number of boreholes	Thickness of Quaternary sediments	Water level (m)	max. Q ($l.s^{-1}$)	q ($l.s^{-1}.m^{-1}$)	k ($m.s^{-1}$)
Pribylina	5	8,0–17,0	1,0–5,5	0,16–11,0	0,07–8,17	$1,0.10^{-5}$– $8,4.10^{-4}$
Vavrišovo	6 5	4,0–14,5 6,6–14,0	1,3–2,2 1,5–6,2	2,6–20,0 2,9–15,0	1,74–8,0 1,35–7,95	$3,5.10^{-4}$– $4,2.10^{-3}$ $3,0.10^{-4}$– $1,1.10^{-3}$
Liptovský Peter	3	4,0–12,0	1,4–3,0	0,6–9,9	0,3–3,8	$5,6.10^{-4}$– $5,8.10^{-4}$

Q – volume discharge, q – specific capacity, k – hydraulic conductivity

Tab. 4 Discharge of springs in Quaternary sediments

Spring locality	Altitude a.s.l m	Discharge $l.s^{-1}$ min	max	average	Observed – time,who
Križan-1 Vavrišovo	720,0	27,7	61,8	41,5	1985–1990, SHMÚ
Križan-2 Vavrišovo	720,0	21,0	58,4	28,1	1985–1990, SHMÚ
Pleso Pribylina	883,0	10,9	52,1	23,3	1985–1990, SHMÚ

total mineralisation (up to 150 $mg.l^{-1}$) than springs flowing out in crystalline complexes. As it has been already mentioned, specific conditions are associated with springs in lower altitudes connected with carbonate "islands". The value of their total mineralisation is variable, but generally it attains about 100 $mg.l^{-1}$. Large springs flowing out in Quaternary sediments as a result of change in hydraulic conditions (springs No. 9 and 10) characteristically reflect already by their primary chemistry the influence of predominant silicate type of rocks of groundwater circulation.

All springs in the catchment display a very low contamination degree, which may be documented by low concentration values of chlorides, nitrates and sulphates, comparable with initial values of infiltrating precipitation water. However, certain anthropogenic influences may be observed in slightly increased sulphate values, especially in springs flowing out in the lowermost part of the catchment (No. 9 and 10).

As it can see on data from Tab. 5, surface waters differ very little in their chemistry in the whole

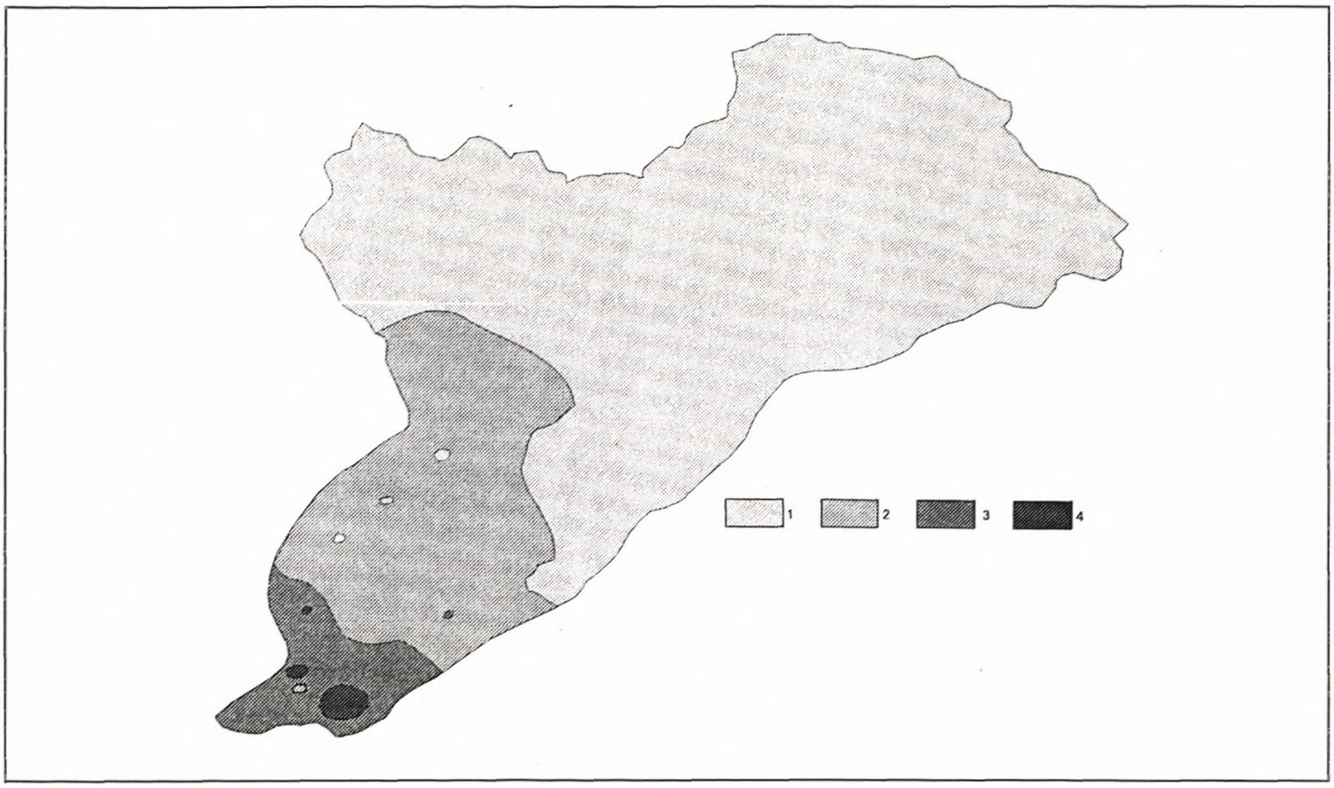

Fig.7: Distribution of sulphate concentration values (mg.l^{-1}) in groundwater. 1: < 10; 2:10-25; 3: 25-50; 4: > 50

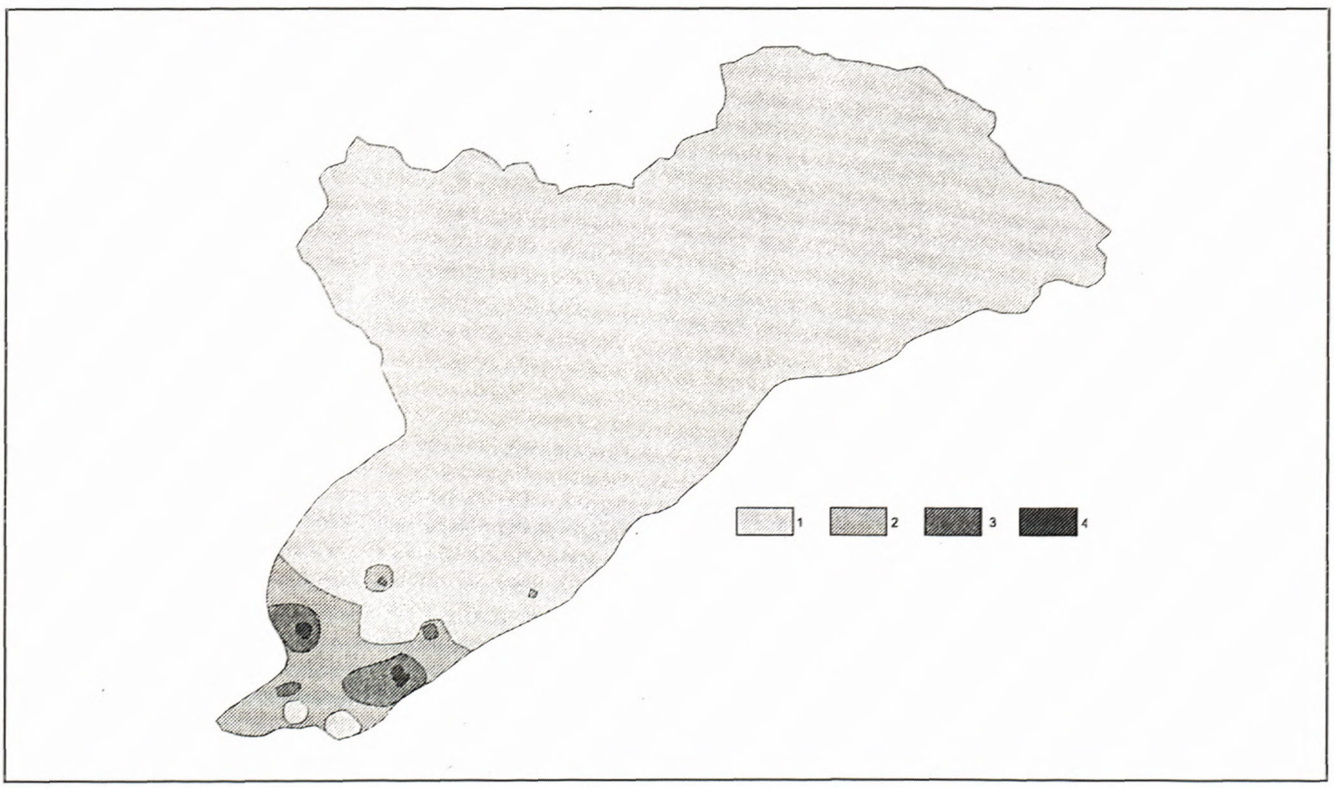

Fig.8: Distribution of nitrate concentration values (mg.l^{-1}) in groundwater. 1: <15; 2: 15-25; 3: 25-50; 4: >50

Tab. 5 Water chemistry in Belá river catchment

Water	pH	TDS	Na	K	NH_4	Ca	Mg	Cl	NO_3	SO_4	HCO_3
		mg . l^{-1}									
■ Snowmelt											
1	4.57	14.7	0.31	0.20	0.59	1.47	0.25	2.93	1.55	4.36	-
2	4.44	10.3	0.32	0.09	0.40	0.81	0.14	2.51	1.32	3.15	-
3	4.70	13.0	0.52	0.10	0.37	1.56	0.36	4.80	0.68	2.45	-
4	4.85	7.6	0.11	0.04	0.91	0.23	0.10	0.70	1.15	2.30	-
Stream											
1 n = 5	6.76	34.4	0.42	0.04	<0.05	4.01	1.85	2.13	1.46	4.77	18.31
2 n = 4	6.61	35.0	0.43	0.02	<0.05	4.01	1.40	2.70	1.53	5.97	16.78
3 n = 5	6.83	47.7	0.80	0.34	<0.05	5.77	1.46	1.77	1.94	7.00	21.97
4 n = 12	7.13	52.2	1.00	0.23	<0.05	7.81	1.73	1.61	1.87	8.27	23.98
5 n = 11	7.00	53.3	1.07	0.35	<0.05	7.89	1.66	1.41	2.09	9.65	22.83
6 n = 4	6.75	44.6	0.80	0.23	<0.05	5.61	1.58	1.91	1.58	6.90	21.36
7 n = 1	8.00	159.8	0.10	0.10	<0.05	33.27	4.13	1.06	3.10	5.76	103.73
8 n = 9	7.57	72.2	1.25	0.31	<0.05	12.17	1.78	1.34	2.59	8.99	33.99
9 n = 9	7.50	78.1	1.54	0.39	<0.05	12.25	2.58	2.23	2.47	10.54	37.79
10 n = 8	7.54	113.2	2.69	0.96	<0.05	17.69	3.89	4.40	4.41	14.37	54.52
□ Spring											
1 n = 4	6.73	50.3	1.08	0.10	<0.05	6.41	1.58	2.52	2.43	6.58	22.89
2 n = 1	7.90	148.0	0.10	0.05	<0.05	30.46	3.40	1.24	2.70	4.53	103.70
3 n = 1	7.45	71.9	1.80	0.50	0.10	8.02	2.43	1.24	0.70	6.17	36.61
4 n = 1	6.80	55.3	1.50	0.10	0.11	6.01	2.92	0.89	0.60	6.17	24.41
5 n = 1	7.45	103.0	1.80	0.40	0.09	14.03	4.86	1.77	1.00	11.52	54.92
6 n = 1	7.80	106.7	1.60	0.30	<0.05	15.23	4.38	0.89	1.60	8.64	61.02
7 n = 3	7.03	61.3	1.63	0.30	<0.05	8.55	2.11	1.24	1.87	7.08	28.48
8 n = 1	7.45	64.3	1.70	0.40	<0.05	8.82	1.70	1.55	2.80	10.29	24.41
9 n = 7	6.97	79.0	1.72	0.56	<0.05	12.39	2.57	1.90	2.94	12.37	36.73
10 n = 2	6.89	89.4	2.20	0.62	<0.05	13.77	3.20	2.75	3.08	12.77	42.16
◇ Borehole											
1 n = 3	6.70	96.8	1.53	0.80	<0.05	14.29	4.46	5.26	3.10	12.08	45.56
2 n = 4	6.74	171.3	5.63	5.90	<0.05	23.40	6.51	9.35	18.91	28.89	58.73
3 n = 4	6.74	150.8	4.20	1.93	<0.05	23.87	5.72	8.78	29.65	25.36	38.98

Note: Data on average snowmelt chemistry (1–3) after VRANA et al. (1989), single sample no. 4 taken 26. 1. 1990. Other chemical analyses were obtained within the frame of realization of the hydrogeological project, described in the report for years 1985–1990 (HANZEL et al., 1990)
n – number of samples

catchment. From the presented chemical components, significant for the indication of water pollution in the relevant land use type (agricultural-recreational to recreational land) are especially ammonium, chlorides, nitrates and sulphates. It is however evident that due to the runoff regime (relatively large discharge of brooks during the whole year) the produced pollution is immediately "diluted" to values approaching the typical background concentration values in "clean" mountainous environment.

Principal changes in water chemistry are caused by anthropogenic influences reflecting in principle the type of land use. The distribution of nitrate and sulphate values (as pollution indicators) in groundwater of the catchment (Figs. 6 and 7) shows that these anthropogenic influences are concentrating in the lower half of the catchment, especially in its lowermost part. This corresponds generally to the T.D.S. value distribution (Fig.6) with the exception of the fact that in the area of the subtatric fault we may find also groundwater outflows with increased T.D.S. values, due to CO_2 saturation, and thus also with naturally increased hydrogencarbonates. Since we are evaluating only the first aquifer, we do not deal with this problem in greater detail.

The lower half of the catchment, belonging to the Liptov Basin, is thus characterised by influences of communal and agricultural type contamination. Areally increased chloride and sulphate concentrations in groundwater of the first aquifer occur only in the lowermost part of the catchment, as it is documented by Figs. 7 and 8. The influence of increased concentrations of contaminants is then reflected also in increased T.D.S. values, locally even exceeding 600 $mg.l^{-1}$, although in undisturbed natural conditions expected T.D.S. values even in the lowermost part of the catchment are only about 100-150 $mg.l^{-1}$. This is supported by T.D.S. values and the character of chemistry of large springs (No 9 and 10) flowing out in Quaternary sediments due to already discussed changes of hydraulic parameters of water circulation rock environment.

Finally it must be stressed that the task of hydrogeology in the next period will be to define, in co-operation with land ecologists, characteristic pollution types of natural water in different land units, distinguished on the basis of land use type. This method may contribute significantly to redefining of distinguished territorial units and thus allow considerably more qualified and effective decision-making in the state's ecological policy.

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Relationship of linear remote sensing data and springs in epimetamorphic late paleozoic rocks

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Abstract:

In the basin of the Eastern Slovak river Hnilec the location of natural groundwater outflows has been correlated with the course of lineaments identified on multispectral, foto-grammetric panchromatic and 2.5 cm "SLAR" radar pictures and by geologic mapping determined fault zones. The relationship between the lineaments and springs was investigated using the geographic information system IDRISI, creating envelope surfaces around the lineaments, with boundaries at the distance of 50, 100 and 150 m. Afterwards, cumulated spring capacity inside the envelope surface of lineament groups, distinguished on panchromatic, multispectral, radar images was compared as well as their number. Direction intervals of lineament divided into 10 ° were compared in the same way.

It has been found that direction interval of 51–60° and 151–160° had the highest "absolute" values of cumulated capacity and spring number, however, after division with the envelope area, aimed at obtaining "relative" values, lineaments of the direction intervals 71–120° appeared in foreground. These are, as it appears, the most open ways for the circulation of groundwater. The west-east direction of these, from hydrogeologic viewpoint well opened lineaments, is consistent with the direction perpendicular to the last regional extension field connected with the subduction of the flysch belt basement under the Western Carpathians during Upper Sarmatian – Pliocene.

Key words: remote sensing - hydrogeology - groundwater - springs - faults - radar - multispectral , panchromatic, images

(2 Figs., 5 Tabs.)

Introduction

Water-bearing fractured rock environment is from hydrogeologic viewpoint, due to its discretion, anisotropy and heterogeneity, a complicated system. Fracture systems and tectonic predisposition of transmissivity play an important role in massifs formed of rocks, as well as in the case of semi-rock Paleogene sediments. Tectonic predisposition of transmissivity often even covers the differences in hydraulic conductivity expected with regard to lithologic types of aquifers. In the first stage of obtaining and capturing groundwater by drilling, the faulting of the massif becomes a factor increasing the risk in successful capture of the sources and complicating representative calculations of filtration characteristics.

Remote sensing became in the last decades an important part of the investigation of fractured environment on regional scale. Recording compact regions, using various apparatus in different spectral ranges of electromagnetic radiation, provides regional information on the position of important fault lines, as well as about the character of the fracturing. Fractured water-bearing environment has so far been investigated by remote sensing especially with the aim to locate hydrogeologic exploitation drillholes, or to evaluate the relationship between the capacity of existing hydrogeologic drillholes and the location, number and orientation of photolineaments in their immediate surroundings (SIDDIQUI – PARIZEK, 1971, GERLACH, 1977, KRUCK, 1977 and 1979, MOORE, 1976, PARRY – PIPPER 1979, TARANIK 1976, HRKAL 1989).

Our attempt at finding statistical correlation relationships between natural groundwater outflows in water-bearing fractured environment of Lower Paleozoic epimetamorphic flysch rocks and the position of photolineaments is, more or less, an inverse task.

Geological characterisation of the studied region

The area of the Spišsko-gemerské rudohorie Mts., within which the studied regionof Volovské vrchy Hills is situated, is the southernmost tectonic unit of the Inner Western Carpathians, termed "gemericum". This tectonic unit is lying in a nappe position on the tectonic unit of the more to the north lying veporicum. The thrust boundary corresponds to the course of the Ľubeník-Margecany line. Gemericum consists of rock complexes from three evolution cycles: Early Paleozoic, Late Paleozoic and Mesozoic. Rock complexes of the Early Paleozoic form almost all of the Hnilec drainage basin, within which there are 510 km^2 of the studied territory. It is a flysch meso-rhythmic sedimentation of sandstones and claystones, with alternating flysch subformations, accompanied by synchronic acid, to a lesser extent also basic volcanism. In the upper part the sedimentation is more varied due to carbonates and lydites. The age of the lower unit – the Gelnica Group - has an estimated stratigraphic span of Upper Cambrian to Lower Devonian (BAJANÍK — VOZÁROVÁ 1982). The result of Hercynian regional epimetamorphism of the above rock complexes are then alternating layers of phyllites and quartzites, metarhyolites and metarhyolite tuffs, in an estimated thickness of 4500 – 8000m.

The above lying Rakovec Group is then a volcanogenic formation characterised by extensively developed subaquatic basic volcanism. Besides phyllites and quartzites, there are mostly metabasalts and metabasalt tuffs. The thickness of the Rakovec Group is estimated in the range of 1500 to 2500 m.

Most important for the formaiton of fragile deformations in rocks of the epimetamorphic Paleozoic of the Spišsko-gemerské rudohorie Mts. was the post-Paleogene stage of geological history of the territory. The formation, course and importance of rupture faults were however controlled by the existence of a basic inhomogeneity - cleavage. The direction of cleavage is almost in all of the territory east-west, only in the area of Smolník-Úhorná it turns to NE-SW (SNOPKO, 1971). This marked, but very isotropic inhomogeneity then determined the character of fragile-deformation effects of later stress fields. Regional deformation field rotated from the Oligocene to the Sarmatian gradually in clockwise direction, from stress direction NW-SE to NE-SW (KOVÁČ et al., 1992, NEMČOK et al., 1993). The resulting extension directions - the direction of pull-apart fractures - are parallel with stress direction and they may be thus assumed in the ranges 141–150°(or 151–160°) to 41–50°. However, this rotation of stress field from NW-SE to NE-SW does not end the evolution of tectonic stress in this territory. In the period from the Sarmatian to the Pliocene, the territory was affected by extension forces related to the development of the Carpathian arc - subduction of the flysch belt basement beneath the Western Carpathian block (RATSCHBACHER, 1991, RATSCHBACHER et al., 1991). The extension has the direction NNE–SSW to NE–SW (20 to 40°), so that open fracture system perpendicular to this system is lying in the direction range 110–130°.

Circulation pathways of groundwater in the studied territory

The ways of groundwater circulation in the hydrogeologic massif of epimetamorphic Paleozoic rocks of the Volovské vrchy Hills is in its basic features determined by the interrelation of water-bearing Quaternary sediments (alluvia, elluvia and delluvial slope debris) and underlying rock basement. While Quaternary sediments are generally ascribed by an order higher transmissivity and pore permeability, Paleozoic rocks are considerably less transmissive with fracture type of permeability. From the results of hydrogeologic survey carried out in this region in 1986–1990 (P. MALÍK – K. VRANA – J. IVANIČKA, 1990) it follows that lithologic differences in the basement rocks do not play an important role in the way of groundwater circulation. The generally accepted assumption of a circulation pathway being predisposed by the interaction of rock environment type and tectonic stress should however reflect better the effects of the plasticity of epimetamorphosed flyschoid sediments, especially phyllites. These rocks should have, in comparison with the more rigid quartzites, more packed fracture systems and thus lower transmissivity. The results of hydrological observations, hydrogeologic drilling and evaluation of spring documentation however do not indicate lower water-bearing capacity of phyllites (maybe with the exception of graphitic phyllites), to the contrary, they indicate 2–8 times higher transmissivity, determined in hydrogeologic drillholes situated in phyllites.

1761 springs and mine waters were documented in the drainage basin of Hnilec in the Volovské vrchy Hills. It is interesting that quartzites, porphyroids as well as non-mine water of the metabasalts have very similar distribution of spring numbers as well as capacities between different spring types, which would indicate relative similarity of circulation conditions in these rock types, forming the drainage basin, as well as the fact that circulation pathways are probably controlled by the direction of tectonic faults in all rock types.

However, since there is the generally accepted opinion of higher water-bearing capacity of quartzites in comparison with phyllites, there was an attempt to quantify this ratio in the case of springs (MALÍK et al., 1990). The ratio the occurrence of quartzites vs. phyllites determined by planimetric analysis is approximately 40% : 60%. If we take into consideration the number of all documented springs and the capacity of all springs, this ratio is 30 : 70%, or 31 : 69%, respectively. After excluding debris springs we obtain for the number and capacity of springs the ratios 36 : 64%, or 33 : 67%, respectively, again not in favour of quartzites. If we exclude also mine water, which can unfavourably affect the statistics by drainage of large mixed units, we obtain the ratios 35 : 65% for the number and 32 : 68% for the capacity of springs, again unfavourable for quartzites. The ratio is also similar for springs exceeding 1.0 $l.s^{-1}$ - 34 : 66%. Generally we may thus state that quartzites display lesser hydrogeologic effects than it would correspond to their ratio to phyllites and we could deduce that their hydrogeologic productivity may be even lower than that of phyllites. However, since these considerations are loaded by imprecision in the determination of relative occurrence of quartzites and phyllites, as well as problematic accurate specification of rock types in the documentation of springs, we conclude than the most important factors of water-bearing capacity are here rather the cover formations and tectonics.

Based on these results, we may evaluate the pre-Quaternary rocks of the Volovské vrchy Hills as a relatively uniform hydrogeologic massif, in which, independently of rock composition, tectonic faults of rupture character produce the decisive and determinative effects on water-bearing capacity. We may thus state that the whole massif is a strongly discretised body with substantially aquiferous fractures and tectonic faults and low-aquiferous rock blocks, which occur among them.

EVALUATED REMOTE SENSING MATERIAL

We consider the circulation of groundwater in Volovské vrchy Hills to be controlled to a greater extent by tectonic predisposition than by lithologic properties of the evaluated territory. From this fact then followed our attempt to find preferred ways of water issue with the help of remote sensing using several types of material.

Air panchromatic images

Classical black-and-white (panchromatic) air images, with an approximate scale of 1 : 30 000, allow a relatively simple identification of basic geodynamic elements. The stereoscopic analysis itself was focused on the study of faults and fractures, slide areas and conspicious approximate relicts of original levelled surfaces. To ensure greater objectivity, stereoscopic interpretation was based on two independent evaluations and comparison of the results. The results were documented on map appendices, on the scale 1 : 25 000 (POSPÍŠIL, 1992)

Radar images

Radar images were taken by a Soviet radar, with the wave length 2.5 cm, on the principle of SLAR (Side Looking Airborne Radar) - "radar bokovogo obzora". During the evaluation of the radar images the absence of complementary data - situation of the air course in terrain - became evident, presenting, due to the applied method of side radar orientation and subsequent progressive distortion of images, considerable difficulties for the location of interpreted results in maps.

Multispectral air images:

Multispectral air images were made by an air multispectral chamber MKF-6M in six spectral ranges:

Channel 1: 460 – 500 nm
Channel 2: 520 – 560 nm
Channel 3: 580 – 620 nm
Channel 4: 640 – 680 nm
Channel 5: 700 – 740 nm
Channel 6: 780 – 860 nm

Air courses during the scanning were approximately parallel in east-west and west-east direction, with appropriate overlapping of the images, allowing stereoscopic evaluation.

From multispectral air images of the Hnilec river basin in the Volovské vrchy Hills, pseudo-coloured multispectral syntheses have been prepared for further interpretation, using electronic mixer and image analyser NAC MCDS 4200F. According to original intents, negative and positive images of the Channel 2, 4 and 6 of MKF-6 should have been used for syntheses, in the following colour combinations:

Channel 2: positive blue

Channel 4: negative green

Channel 6: negative red

When preparing syntheses according to this scheme it became evident that the quality of existing negatives would not yield required results. These technical reasons led to a change in the colour and channel combination in multispectral synthesis: to ensure that the synthesis would not be too dark in the final appearance, positive version of the channels were preferred and the synthesis scheme was as follows:

Channel 2: positive blue

Channel 3: positive green

Channel 6: positive red

Thus, a pseudo-natural colour combination was selected, preserving the succession of colours in spectrum (blue-green-red) and simultaneously shifting them into higher wave lengths (red colour was attached to the infra-red range invisible to the human eye). Therefore, the resulting colour appearance of the synthesis corresponds approximately to colour spectrozonal images.

Another source of adverse effects in the syntheses, besides the above mentioned difficulties with the too high optical density of negatives, was also too high optical steepness (contrast) of negatives of channels 2, 3 and 4. Too contrasting negatives did not allow to create a full range of colour shades for the synthesis (POSPÍŠIL, 1992)

EVALUATION AND ANALYSIS OF LINEAR REMOTE SENSING DATA AND METHOD OF THEIR CORRELATION WITH GROUNDWATER ISSUES

Using the module DIGITIZE of the software package ROCKWARE, rivers, spring co-ordinates and fault lines were digitised from the geological map, panchromatic images and radar images. Digitised data were then transferred for the purpose of drawing into the software SURFER and transformed into the analytical program IDRISI, producing **raster** maps of springs and lineaments from each basic material. The lineament maps were further divided to obtain 18 maps for each method of lineament determination - separately for panchromatic, multispectral, radar images or faults from geological map. Individual maps always showed lineaments in a direction range. The ranges were divided at 10° from the range 1°– 10° to the range 171°– 180°. For each of these maps, envelope curve maps about relevant lineaments were created, limiting an area of up to 50 m, up to 100 m and up to 150 m about the lineament. From thus prepared material, an intersection has been made with the map showing the distribution of springs, obtaining the numbers of springs and later on cumulated spring capacities within the surfaces of up to 50 m , 100 m and 150 m from the lineaments or fault lines. Since surfaces about the lineaments with different directions overlapped at certain places, some springs were recorded in both surfaces and thus may have been counted several times into the total number of springs and their capacities summed into cumulated capacity. Since the aim was not to determine accurately the boundaries between the surfaces about lineaments with different directions, and the number of double-counted springs was not significant, this fact should not affect the general conclusions. From the above description of the construction of maps it follows that the surfaces and thus also the numbers of springs are more accurate at a distance of up to 50 m from the lineament and with increasing distance they become more cumulated.

RELATIONSHIP BETWEEN THE OCCURRENCE AND CAPACITY OF NATURAL GROUNDWATER ISSUES AND THEIR POSITION IN RELATION TO THE INTERPRETED LINEAMENTS

We based our investigation of the assumed relationship of groundwater issues to zones of more intensive faulting of the rock massif, which from the bird's eye perspective may appear as lineaments identifiable on air images of the territory, on the following premises:

1. if the groundwater issues were not associated with preferred zones, the total number of 1761 springs would be distributed more or less uniformly

on the whole area of the Hnilec river basin in the Volovské vrchy Hills (510.0 km^2)

2. if the spring issues were not associated with fault zones, the total spring capacity in the river basin (845.85 $l.s^{-1}$) would be more or less uniformly distributed on the whole area of the river basin.

On the surface limited by the distance of up to 50 m from faults determined by geological mapping (this surface is 51.03 km^2, which is 10.00% of the total area) there are 337 springs, which is 19.13% of the total number of springs in the river basin. Assuming homogeneous distribution of springs, the relative parts of surface and spring number should be approximately the same in value. The determined 1.913 times higher relative number of springs near fault lines determined from the geological map indicates certain relationship of spring occurrences to faults. Similar is the case of the comparison of spring capacities at the distance of up to 50 m from fault lines of the geological map. Total capacity of these springs (200.29 l.s-1) represents 23.67% of the total capacity of all springs in the river basin, and it is thus 2.36 times higher than it should be at uniform distribution of spring capacities on the whole studied territory.

The surface of up to 50 m from lineaments interpreted from panchromatic materials represents 30.92 km^2, and thus 6.06% of the Hnilec river basin surface in the Volovské vrchy Hills. 219 springs are flowing off on this area, with a total capacity of 128.4 $l.s^{-1}$, i.e. 12.43% of the number of springs and 15.18% of the total capacity of all springs on the studied territory. In the case of number of springs the real number vs. expected numbers at uniform distribution is 2.05 and in the case of spring capacities it is 2.50.

Multispectral images are, due to the total length of lineaments identifiable from them (and by the surface limited by 50 m distance from them), together with radar images, the most important ones. In contrast to radar images - and, of course, also panchromatic images and geological map - the determined ratios of expected (at uniform distribution) and real number of springs - 2.52, and of the expected and real capacity - 2.75 - are however somewhat higher than these ratios at lineaments determined from other materials. On a surface of 70.91 km^2 (13.90% of the investigated area) there are 617 springs (35.03% of the total number), with a total capacity of 323.4 $l.s^{-1}$ (38.23 % of the total capacity).

In the case of radar images these ratios have the values of 2.02 for the number of springs and 2.38 for their total capacity. Lineaments interpreted from radar images have the area of up to 50 m distance largest of all (86.22 km^2 or 16.90%), but the number of springs is here a little lower than at lineaments from multispectral images (602 springs, i.e. 34.18%) and their total capacity (341.3 $l.s^{-1}$, or 40.35%) is only a little higher.

We may thus generally state that for surface boundaries at the distance of 50 m from lineaments identified from various materials, the ratios of the real number of springs vs. the number of springs expected according to the size of area at assumed uniform spring distribution on the whole surface of the studied territory is about the double (in average 2.12) and the ratio of the real total capacity of these springs and total capacity expected according to the surface size of the area at their uniform distribution on the whole studied territory vary about two-and-a-half multiple (in average 2.50). This indicates thus a relationship between the location and capacity of the spring issues and the location of the lineaments. At first comparison of the successfulness of different methods or materials for the identification of lineaments for the areas of up to 50 m from lineaments, the best appears to be the relationship to lineaments interpreted from multispectral images. The ratio of real and expected numbers of spring on these areas is 2.52 (arithmetic mean of the other three identification materials is 1.995) and for the capacity of these springs 2.75 (other three methods – 2.15).

From the obtained results it may be inferred that with increasing distance of area boundaries from the lineaments the total number of springs as well as total capacity increases, but generally not as rapidly as the surface of the areas. From this it follows that the ratio comparing real and expected values of these quantities with increasing distance from the lineament (fault) decreases. This means that spring issues are probably mostly related to narrow zones which could be identified with relatively high precision. For the comparison of successfulness of each lineament identification from different materials there were compiled tables 1 and 2, eliminating the differences in length and thus also in the surface of areas about identified lineaments by introducing average number of springs and average spring capacity on 1 km^2 of the area about the lineaments.

When comparing average number of springs and average spring capacity on 1 km^2 of the area about lineaments (from tables 1 and 2) we may again observe the above mentioned fact that average number as well as capacity of springs decreases with increasing size of the area. We assume that this confirmed the consistence of the pathways of preferred groundwater circulation and issue with the course of identified lineaments, while considerable precision of their localisation has been shown as well. When comparing the capacity to record the most of groundwater issues with highest capacity according to tables 1 and 2 the best appear to be again lineaments from multispectral images. Since from the above said it may be inferred that the most significant is the distance range of up to 50 m from a lineament, in the following we shall also deal with the comparison of values obtained from various

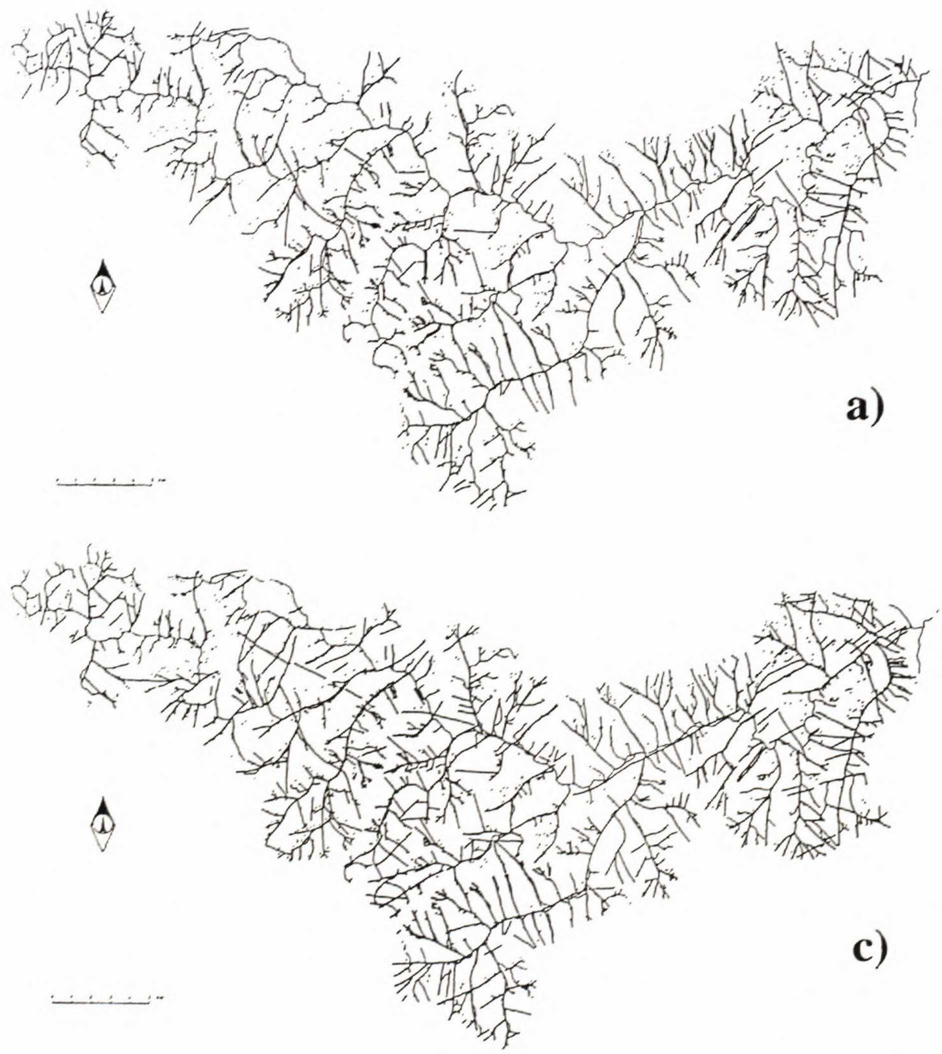
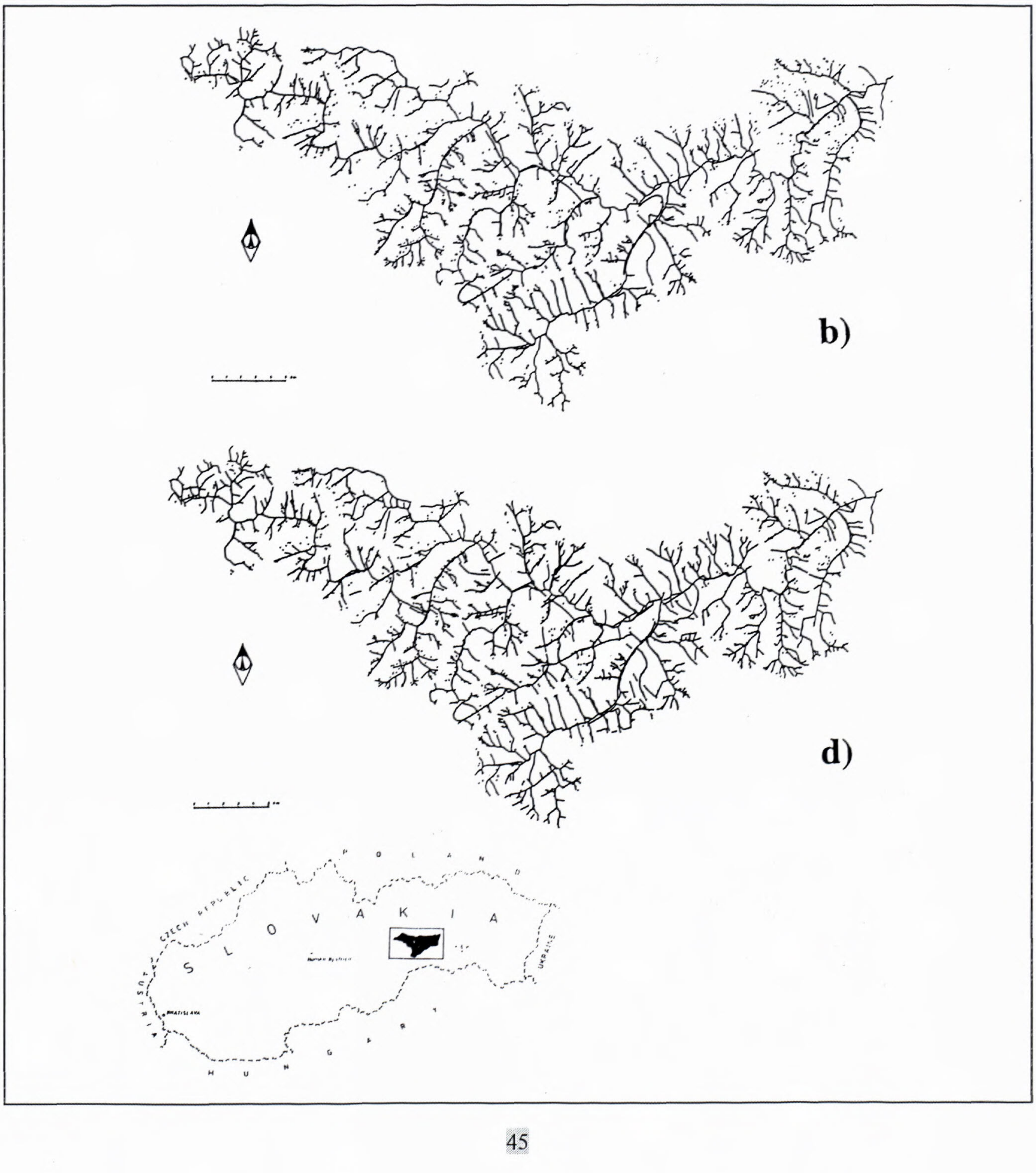


Fig. 1 Investigated area of the river Hnilec basin, position of surface streams, springs and:
a) fault lines according to geological map in 1:50 000 scale, b) lineaments derived from panchromatic images, c) lineaments derived from multispectral images, d) lineaments derived from radar (SLAR) images

identification material for this range: total number of spring on the surface of 1 km^2 of the area is for all materials 7.34, for "multispectral lineaments" it is 8.70 and for lineaments from other materials 6.89.

Average spring capacity sum from 1 km^2 of the "50 m area" for lineaments of all materials is in average 4.15 l.s^{-1}, for lineaments obtained by the interpretation of multispectral images 4.56 l.s.$^{-1}$ and for other lineaments is the average 4.01 l.s^{-1}. Multispectral images, or from them interpreted lineaments, do not display length dominance (lineaments from radar images are by almost 20% longer) nor preference of lineament directions, which would be neglected by lineaments from other materials (see previous part). Multispectral lineaments are rather characterised by uniform distribution of lineaments into direction ranges. We thus assume that their relatively higher effectiveness is a result especially of the precision of localisation of



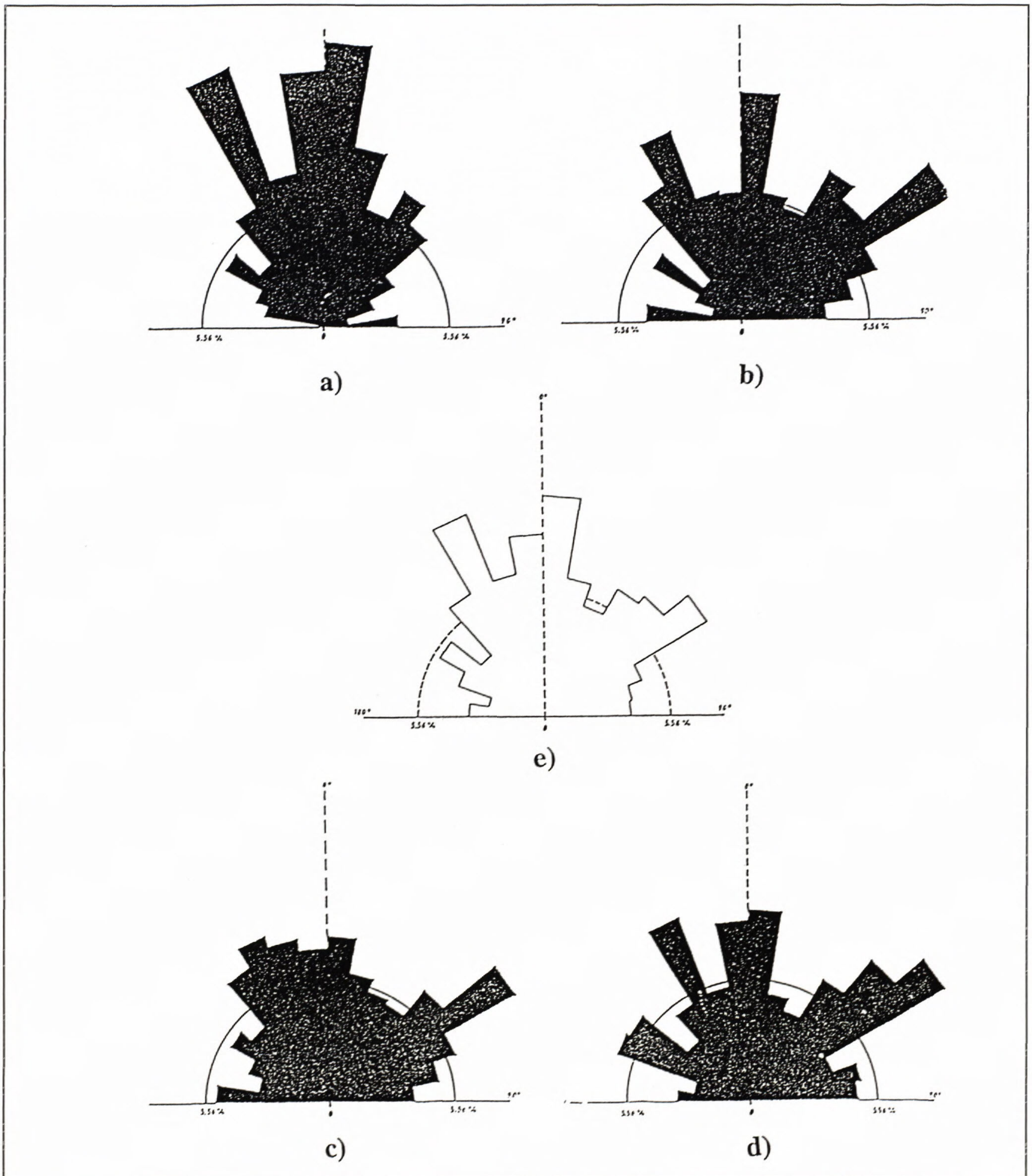


Fig. 2: Preferences in direction of lineaments, derived from: a) fault lines according to geological map in 1:50 000 scale, b) lineaments derived from panchromatic images, c) lineaments derived from multispectral images, d) lineaments derived from radar (SLAR) images, e) average values of all methods. Interval of lineament directions are divided in 10^o intervals (0^o– north, 90^o– east, 180^o– south),figures are made to compare relative values of cumulated lengths of lineaments belonging to separate direction intervals. Semicircle represents average value, which can be expected in the isotropic case - equal preferences of all direction intervals.

lineaments and of not loading of the lineament network with lineaments having little or no relevance as preferred groundwater circulation ways (which probably happened in the case of radar images).

RELATIONSHIP BETWEEN LINEAMENT DIRECTION AND OCCURRENCE AND CAPACITY OF GROUNDWATER ISSUES

When comparing the hydrogeologic significance (openness for groundwater circulation) of different direction ranges of lineaments determined by the interpretation of different materials, we also used the original premise of homogeneity – uniform distribution of the number of total capacity in relevant areas for all lineament direction ranges. Since direction ranges were divided at 10°, the respective percentage of number or capacity of springs at their uniform distribution in all ranges would be 1/18, i.e. 5.56% for each range.

Since total spring capacities as well as numbers within the 50, 100 and 150 m areas in general follow the relative area surface within the ranges (1–10° to 171–180°), in view of the considerably variable surface of the areas it was necessary to evaluate the hydrogeologic significance, i.e. the probable openness of various lineament directions for groundwater circulation by relative quantities - ratios of the percentage of the spring numbers or capacities and the percentage of the relevant area surface.

This evaluation of the ratio of spring number percentage and relevant area surface percentage yielded quite different preferences for different direction ranges than those recorded in the evaluation of "absolute numbers". The highest values of the above ratio are obtained from relative spring occurrences about faults determined by geological mapping. Tab.4 shows that the succession of first three direction ranges is constant for all area sizes: 1. 91–100°, 2. 11–120°, 3. 161 – 170°, 4. 121–130° and 5. 171–180°

The value of relative spring occurrence attains here 1.85 and the first three ranges have the highest average values from all evaluated direction ranges at all lineaments. Lineaments identified from panchromatic images show significant changes in

Tab. 1 Comparison of the number of springs in a 1 km^2 area limited by various distances from a lineament (fault) for different identification methods of lineaments

Area at a distance	Number of springs on 1 km^2 area in relevant distance from a lineament identified from:			
	geologic map	panchromatic images	multispectral images	radar images
up to 50 m	6,604	7,080	8,701	6,982
up to 100 m	6,066	5,932	7,060	5,939
up to 150 m	4,847	5,052	5,828	5,230

Tab. 2 Comparison of average spring capacities on 1 km^2 area limited by various distances from a lineament (fault) for different lineament identification methods.

Area at a distance from lineament of:	Spring capacity on 1 km^2 of the area in relevant distance from lineament identified from:			
	geological map	panchromatic images	multispectral images	radar images
up to 50 m	3,925	4,154	4,561	3,959
up to 100 m	3,441	3,063	3,521	3,389
up to 150	2,691	2,792	2,864	2,810

the succession of direction ranges with changing area boundary distances from the lineaments. The leading position in the succession according to the relative occurrence is relatively constant with direction intervals of 21–30°and 51–60°, relatively significant are perhaps also the ranges 51–60°and 91–100°.

Lineaments identified from multispectral images in relation to the value of relative spring number occurrence show clear preference of the direction range 121–130°. Second place is then occupied by the direction 81-90° and other preferences are more ore less dispersed, or there are preferred secondarily the ranges 41–50° and 171–180°.

The direction range 121–130° is clearly leading also in the case of lineaments identified from radar images. At a distance then follows the preference of the direction 101–110° and we may also mention secondary preferences of direction ranges 171–180°, 131–140° and 61–70°. The results of the evaluation of the spring occurrence percentage and relevant area surface percentage ratio are listed for all lineament types in Tab.3.

In general we may thus evaluate as most occupied by springs the direction range 121–130°, taking the first place in multispectral as well as radar lineaments and having a firm leading position also among tectonic lines determined by geological mapping. With the exception of lineaments derived from panchromatic images, the direction 171–180° has also considerable common preference, other ranges of direction do not have many simultaneous preferences at various lineament types.

If we evaluate the ratio of total spring capacity percentage and relevant area surface percentage in the areas of up to 50, 100 and 150 m about faults from geological map as well as lineaments identified from panchromatic images, we obtain, in comparison with lineaments from multispectral and radar images, higher numerical values of this ratio. Fault lines have besides this a clearly determined preferential relation to specific direction ranges, which does not change even with increasing area. In the first place they are faults in the direction range 61–70°, then 111–120° and third is the direction 31–40°. Secondary are preferential orientations in direction ranges 151–160° and 171–180° (see also Fig. 2).

Lineaments from panchromatic images have with fault lines in common only the preferential orientation to the direction range 111–120°, besides this preferred directions are 51–60° and 91–100°. Less preferred is the orientation in the range 101–110°and, similarly as in the case of fault lines, the preference of the direction 151-160° is here less significant - it is one of the few direction ranges which - with their significantly preferred "absolute values" of spring numbers and capacities - did not get lost among sub-average values after the introduction of relative capacities.

The values of relative total capacities of springs occurring in relevant areas about lineaments interpreted from multispectral images and their differences are lower than in the above mentioned cases. A significantly preferred range is 41–50°, followed by 101–110°. Complementary to the clearly preferred direction 101–110° are preferences of the ranges 81–90° and 111–120°, along with 121–130°.

The main direction ranges of "radar lineaments", on the surface of which there is relatively highest total spring issue capacity, are 71–80° and 101–110°. Secondarily preferred are then the directions 121–130° and 61–70°. These results can be found in Tab. 4.

Along with the evaluation of the ratio of total spring capacity percentage and relevant surface percentage, useful for the determination of hydrogeologic significance of different direction ranges may be also the value of median for the capacity of springs occurring in relevant area of the direction range. A common feature of the evaluation of hydrogeologic significance of different direction ranges using median of the capacity of springs occurring within areas up to 50, 100 and 150 m is the common preference of the range 151–160°. Even though this direction does not always appear on leading preferential places, it is nevertheless present in preferences of all lineament types according to material from which they were identified. Besides this it may be stated that "multispectral" and "panchromatic" lineaments have a common feature in their preference of the range 81–90°. Considering that the median of the set of all 1761 documented spring in the Hnilec river basin in the Volovské vrchy Hills is 0.235 $l.s^{-1}$, we may state that springs related to the most preferred direction intervals in Tab.5 really indicate the presence of more open circulation ways of groundwater.

Tab. 3 First 7 lineament direction ranges (identified by various methods) with greatest values of the ratio of relative spring occurrence number percentage vs. area surface percentage at a distance of up to 50, 100 and 150 m from the lineament - first datum in the column shows the value of this ratio in the area of up to 50 (100, 150) m for the relevant direction range, the second datum shows the order of precedence of the range in the relevant range (50, 100 or 150) of the area

Direction ranges of lineaments	Faults from geological map			Panchromatic images			Multispectral images			Radar images		
	50 m	100 m	150 m	50 m	100 m	150 m	50 m	100 m	150 m	50 m	100 m	150 m
1-10°												
11-20°							1,059 7	1,091 5				
21-30°		1,010 6		1,426 1	1,321 2	1,155 5			1,025 7			
31-40°												1,078 7
41-50°			1,090 6	1,384 2	1,422 1	1,160 4	1,075 5	1,189 2	1,128 4			
51-60°				1,146 6	1,225 3	1,170 3		1,059 7				
61-70°	1,122 6									1,249 4	1,314 2	1,343 3
71-80°										1,049 7	1,029 7	
81-90°							1,150 2	1,165 3	1,192 2			
91-100°	1,854 1	1,515 1	1,552 1	1,269 3	1.223 4	1,279 1		1,129 4	1,137 3			
101-110°						1,146 6	1,069 6			1,282 2	1,158 5	1,149 5
111-120°	1,618 2	1,467 2	1,517 2	1,191 4	1,206 5	1,180 2	1,088 4		1,099 5			
121-130°	1,372 4	1,250 4	1,185 4		1,193 6		1,398 1	1,432 1	1,388 1	1,433 1	1,577 1	1,512 2
131-140°										1,203 5	1,208 3	1,189 4
141-150°												
151-160°				1,160 5	1,141 7	1,131 7						
161-170°	1,560 3	1,302 3	1,279 3							1,197 6	1,086 6	1,575 1
171-180°	1,288 5	1,088 5	1,127 5				1,131 3	1,066 6	1,039 6	1,262 3	1,181 4	1,135 6

Tab. 4 First 7 lineament direction ranges (identified by various methods) with greatest values of the ratio of total spring capacity percentage vs. area surface percentage in the area of up to 50, 100 and 150 m from the lineament - first datum in the column shows the value of this ratio in the area of up to 50 (100, 150) m for the relevant direction range, the second datum shows the order of precedence of the range in the relevant range (50, 100 or 150) of the area.

Direction ranges of lineaments	Faults from geological map			Panchromatic images			Multispectral images			Radar images		
	50 m	100 m	150 m	50 m	100 m	150 m	50 m	100 m	150 m	50 m	100 m	150 m
1-10°	1,116 6	1,072 6										1,128 7
11-20°							1,112 6					
21-30°												
31-40°	1,822 3	1,610 3	1,335 4							1,109 6		
41-50°				1,141 6	1,154 7	1,073 6	1,913 1	1,765 1	1,684 2		1,161 6	
51-60°			1,192 7	2,491 2	2,168 3	2,530 1		1,533 3	1,336 6			
61-70°	5,013 1	3,381 1	2,870 1							1,039 7	1,922 2	1,685 3
71-80°										2,621 1	1,960 1	1,716 2
81-90°							1,202 5	1,256 7	1,553 3			
91-100°				2,410 3	2,263 2	1,766 4		1,330 6	1,225 7			
101-110°				1,796 4	1,430 4	2,223 2	1,660 3	1,751 2	1,906 1	1,896 2	1,777 3	1,831 1
111-120°	2,376 2	2,011 2	2,291 2	3,078 1	2,457 1	1,900 3	1,680 2	1,430 4	1,353 5			
121-130°							1,110 7	1,346 5	1,371 4	1,660 3	1,588 4	1,551 5
131-140°											1,164 5	1,243 6
141-150°			1,135 6		1,230 5							
151-160°	1,346 5	1,308 4	1,449 3	1,202 5	1,217 6	1,180 5				1,197 4	1,067 7	
161-170°												1,589 4
171-180°	1,420 4	1,122 5	1,253 5				1,212 4			1,175 5		

Tab. 5 First 7 lineament direction ranges (identified by various methods) with greatest median of spring capacity in the area of up to 50, 100 and 150 m from the lineament - first datum in the column shows the value of the spring capacity median ($l.s^{-1}$) in the area of up to 50 (100, 150) m, the second datum shows the order of precedence of the range in the relevant range (50, 100 or 150) of the area.

Direction ranges of lineaments	Faults from geological map			Panchromatic images			Multispectral images			Radar images		
	50 m	100 m	150 m	50 m	100 m	150 m	50 m	100 m	150 m	50 m	100 m	150 m
1-10°	0,290 6	0,280 5	0,265 5		0,250 4	0,250 5-7						0,275 7
11-20°	0,270 7											
21-30°												
31-40°							0,230 6		0,230 7			
41-50°				0,260 5		0,250 5-7						
51-60°			0,260 6	0,250 6	0,240 5	0,250 5-7		0,250 6	0,250 6	0,350 4	0,350 2-3	
61-70°	0,950 1	0,805 1	0,550 2							0,440 2	0,320 5	
71-80°						0,380 1						
81-90°	0,325 5			0,380 2	0,380 1-2	0,325 3	0,320 2	0,350 2	0,340 1		0,290 7	0,280 5-6
91-100°				0,620 1	0,380 1-2	0,330 2						
101-110°			0,220 7				0,300 3	0,590 1	0,300 3	0,615 1	0,350 2-3	0,520 1
111-120°	0,445 3	0,460 2	0,585 1				0,335 1	0,335 3	0,295 4			
121-130°					0,230 6			0,310 4	0,310 2	0,300 7	0,300 6	0,305 4
131-140°		0,240 6										0,280 5-6
141-150°				0,365 3		0,305 4				0,345 5	0,335 4	0,350 3
151-160°	0,500 2	0,420 3	0,480 3	0,330 4	0,320 3		0,280 4-5	0,280 5	0,280 5	0,420 3	0,420 1	0,380 2
161-170°		0,210 7		0,225 7	0,225 7							
171-180°	0,435 4	0,300 4	0,295 4				0,280 4-5			0,330 6		

CONCLUSION

When averaging the percentages of length preferences of lineaments identified from all four materials, we obtain a dominance of direction intervals 151–160°, further the directions north-south (1–10° and 171–180°) and the range 51–60°. From average values of the per cent occupation of total lengths in the different direction ranges there is also inferred an absence of a greater number or of longer lineament sections in the direction ranges 61–110°. However, it must be stressed that in any of the materials from which the position of the lineaments was determined these are narrow direction zones, in which there are lineaments, while these direction zones are, when comparing the sums of the lengths of in a direction zone present lineaments, sharply separated from neighbouring direction zones.

The relationship of the position and capacities of spring issues to the position of lineament is supported by the fact that for boundaries of studied areas of up to 50 m from lineaments identified from various materials, the ratios of real number of springs vs. number of springs expected according to relevant size of area surface, assuming uniform distribution of springs on the whole surface of the studied territory, vary approximately about the double (in average 2.126) and the ratios of the real total capacity of these springs and total capacity expected according to the size of relevant area surface at the assumption of uniform spring distribution on the whole surface of the studied territory, vary approximately about two-and-a-half multiple (in average 2.502).

Comparing the successfulness of different methods, or materials for the identification of lineaments in areas of up to 50 m from lineaments, the most frequent appears to be the relationship to photolineaments interpreted from multispectral images. For the number of springs in these areas the ratio of real and expected value is 2.520 (arithmetic mean of the other three identification materials is 1.995) and for the capacities of these springs it is 2.750 (other three methods - 2.149-multiple). With increasing distance of area boundaries from the lineaments the total number as well as total capacity of springs occurring inside the areas increase, but in general not as rapidly as the surface of the areas. The ratio comparing real and expected values of these quantities with increasing distance from the lineament (fault) decreases. Spring issues are therefore probably mostly related to narrow zones, which could be identified with great precision, depending from the used image material. The most successful interpretation material - multispectral images, or lineaments interpreted from them, do not show length dominance (lineaments from radar images are almost by 20% longer) nor preference of lineament directions, which would have been neglected by lineaments from other materials (see previous part)."Multispectral lineaments" are rather characterised by uniformity of the distribution of lineaments into direction ranges. We thus conclude that their relatively higher effectivity is a result of the precision of lineament localisation and of the lineament network not being loaded by lineaments which have little or no significance as preferred groundwater circulation pathways.

In the case of multispectral images the interpreters declared a number of technical errors (too high optical steepness (contrast), too high optical density, damage by colour), making the interpretation more difficult. In spite of this we value multispectral images as material capable of providing the most comprehensive and from the hydrogeologic viewpoint most reliable information on the course of lineaments indicating fault zones, to which groundwater issues could be related. This means that these materials, or this method of scannig of the territory, using suitable air carrier, at suitable distribution of air courses and taking into consideration all technical faults, especially in regard to the quality of recorded material, is the most suitable for solving equivalent problems.

"Relative" values of the evaluation of hydrogeologic preference of different direction ranges force into background the directions NE-SW, NW-SE, as well as N-S, and bring into foreground in length (or area) little represented lineaments of east-west direction, especially the ranges 101–110°and 11–120°, less 91–100° and 81–90°. However, even at "relative values" some in length more frequently represented directions do not fall into background: in preferences according to the ratio of total spring capacity percentage and relevant area surface percentage, at lineaments identified from multispectral and panchromatic images, the ranges 41–50° and 51–60° appear as well. In the evaluation of lineaments according to median of the capacity of springs occurring in relevant areas about the springs, there is a common, even though not the most significant preference of the direction range 151-160° for all lineament types. The decreased median value of water temperature for all lineament types in this direction range indicates also deeper circulation of groundwater in fault zones of this direction.

We assume that the majority of other identified lineaments has its geological-tectonic basis in fragile stress strike-slip deformations. These are connected with significant deformation faults, manifested in the surroundings of faults and "making visible" especially lineations of the "Carpathian" NE-SW direction. Besides this, east-west extension zone directions are not only parallel with the air courses during scanning of the territory, but they are parallel also with the general direction of lithological boundaries in the epimetamorphic massif. Therefore we assume that the determined lineaments in the direction ranges of 101-120° (81-100°) have not been exhaustively documented on the studied territory and for their identification it would be necessary to interpret images (especially radar) obtained by scanning in several, preferably perpendicular flying directions. These lineaments, indicated by increased median of the capacity of springs occurring in their immediate surroundings as well as increased values of the ratio of total spring capacity from relevant areas vs. surfaces of these areas represent an important anisotropy and groundwater circulation direction. We may however state that preferred west-east direction of open groundwater circulation pathways is consistent with pull-apart rupture faults, formed due to effect of extension forces related to the development of the Carpathian arc - subduction of the flysch belt basement under the Western Carpathian block (RATSCHBACHER 1991, RATSCHBACHER et al. 1991) in the time of Sarmatian to Pliocene.

In the relevant Hnilec river basin in Volovské vrchy Hills, built predominantly of epimetamorphic Paleozoic rock with fracture permeability the identification of preferred lineament directions (fault and fractures) with higher permeability is an important piece of knowledge for the prospection for groundwater bound to this rock environment. Situating hydrogeologic drilling to the immediate surroundings of such zones results in increased probability of obtaining higher exploitable quantities of groundwater. It is also important to consider increased risk of encountering a permeable tectonic fault with highly confined groundwater table of east-west direction, or in the direction range 151–160° and 41–50° during mining and tunnelling works in this region. To the contrary, when making underground galleries with the aim of capturing the greatest possible quantity of groundwater for supplying drinking water at lowest costs, is the optimum way to situate the gallery perpendicularly to the identified lineaments of above mentioned directions.

The method applied in the presented work may be used on any territory. As it is inferred by the comparison of materials for the interpretation of photolineaments, the most suitable for the interpretation of lineaments with hydrogeologic significance appear to be multispectral images.

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Geochemical Atlas of Slovakia – Groundwaters, Preliminary Results

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Abstract:

Within the framework of the project "Investigation of Environmental Geofactors" 1991-1995 there has been realised the task "Geochemical atlas of Slovakia". In the part focused on groundwater, 16 300 samples (sampling density 1 smpl. per 3 sqkm) were analysed for T.D.S., pH, aggr. CO_2, SiO_2, Na, K, Mg, Ca, NH_4, F, Cl, NO_3, SO_4, HCO_3, PO_4, Fe, Mn, Li, Sr, Zn, Cu, Cd, Pb, Cr, Hg, As, Se, Tl, Sb, Al, Ba, COD - Mn. The task has been designed to provide comprehensive background information on the distribution of components and elements in groundwaters of Slovakia.

Key words: groundwater chemistry, mapping, geochemical anomalies, regional hydrogeochemistry

(3 Figs., 1 tab.)

Introduction

The project entitled "Investigation of Environmental Geofactors" (1991–1995) includes the task "Geochemical atlas of Slovakia". This task is aimed at the compilation of a geochemical atlas of the Slovak Republic, on the scale 1 : 1 mil., during the period 1991–1995, along with maps of geochemical anomalies on the scale 1 : 200 000.

The investigations are focused on the evaluation of concentrations and distributions of chemical elements, including toxic ones, in stream sediments, groundwaters, rocks, soils and forest biomass. The evaluation is aimed also at the total natural radioactivity of the territory and of the constituting elements (K. VRANA, 1992).

The co-ordinator of the project is the Dionýz Štúr Institute of Geology in Bratislava, with the participation of 10 further institutions dealing with natural sciences. From the beginning of the project, the solution of all methodological aspects has been consulted within IGCP No. 259 – International Geochemical Mapping, from 1993 IGCP No. 360 – Baseline Geochemical Mapping (A.DARNLEY, 1994).

One of the most important results of regional geochemical mapping will be groundwater chemistry, which is intended to be published as a separate volume. This paper informs on the methodology of hydrogeochemical mapping and the preliminary results. The final results will be published at the beginning of 1996.

Samples and analytical methods

Hydrogeochemical mapping is based on groundwater sampling of the first water-bearing horizon (springs, wells, drillholes) and its aim is to provide an idea of regional distribution of ecologically and hydrologically most important elements, components and parameters on quantitative basis. In the interpretation the aim is to evaluate the role of primary and secondary factors in the formation of water chemistry on regional scale. The aim is thus to provide time-limited information on the groundwater chemistry of Slovakia, taking into account geochemical criteria of water-quality interpretation.

The water was sampled into polythene bottles from objects according to valid water-sampling regulations, with appropriate adjustment to relevant laboratory requirements. Sampling density is 1 sample per 3 sqkm. Besides natural springs with large capacity, there are sampled also captured springs, dug wells and drillholes, which are used actively. It is evident that regions differ from each other as to the character of sampled objects and real sampling density, due to hydrogeological conditions of the territory.

During similar hydrogeochemical mapping (e.g. P. LAHERMO et al., 1990) groundwater samples are filtered through membrane filters. In our case, samples were filtered through 0.45 mm membrane filters.

Directly in the field all unstable components were fixed and water temperature, pH, conductivity, dissolved O_2, free CO_2 (acidity) and alkalinity were measured. Other components were determined in the laboratory.

The project assumed that a wide range of elements and components (Tab. 1) would be determined in the INGEO laboratory in Žilina, using standard methods for lower detection limits, especially in the case of metals. The control of the laboratory has been secured by the lab's participation in domestic and foreign control tests.

Tab. 1 Analytical processing of hydrogeochemical samples (ppm)

Element Component	Analytical method	Detection limit
Na	AAS-F	100,00
K	AAS-F	100,00
Mg	CT	1000,00
Ca	CT	1000,00
SiO_2	SPFM	500,00
NH_4	SPFM	50,00
F	ISE	100,00
Cl	T	100,00
NO_3	ITPH	500,00
SO_4	ITPH	300,00
HCO_3	(A-B)T	100,00
PO_4	SPFM	50,00
Fe	AAS-F	5,00
Mn	AASF	5,00
Li	AAS-F	2,00
Sr	AAS-F	10,00
Zn	AAS-F	1,00
Cu	AAS-ETA	0,50
Cd	AAS-ETA	0,.50
Pb	AAS-ETA	1,00
Cr	AAS-ETA	0,50
Hg	AAS-CV	0,20
As	AAS-MHS	1,00
Se	AAS-MHS	1,00
Tl	AAS-ETA	5,00
Sb	AAS-MHS	0,20
Al	ICP-OES	10,00
Ba	AAS-F	100,00

AAS-F: flame atomic absorption spectrophotometry, CT: complexometric titration, SPFM: spectrophotometry, AAS-CV: atomic absorption spectrophotometry - cold vapour, AAS-MHS : atomic absorption spectrophotometry - mercury hydride system, (A-B)T: acid-base titration, T: titration, ISE : ion-selective electrodes, AAS-ETA: atomic absorption spectrophotometry-electrothermic atomisation, ITHP: isotachophoresis

Tl has been omitted during the work on the project from the studied association, since Tl has not been determined in amounts above the detection limit in any of the first 3000 samples.

Preliminary results and discussion

The results are interpreted by a team of authors of the co-ordinating institution. The basis will be the compiled maps, a detailed mathematical-statistical data analysis, systemisation diagrams, and hydrogeological as well as hydrological knowledge of the Slovak territory will be taken into account too.

The basic input of the interpretation part will be the text of explanations of Geochemical Atlas, part Groundwater, which, besides newly obtained data, will summarise also important available results of hydrogeochemical mapping of the regions on the Slovak territory. It will include also available information obtained from groundwater quality monitoring project on the Slovak territory.

The Geochemical Atlas will be constructed on the scale 1 : 1 000 000, the geochemical-ecological maps on the scale 1 : 200 000. A part of the obtained information will be displayed in additional maps on various scales.

Geochemical data will be presented in the atlas as follows:

- single-element coloured maps constructed on the principle of moving median (moving median maps) - they will represent regional variations of element contents
- single-element black-and-white point maps (e.g. display of absolute element concentrations, from which over 75% are below detection limit).
- derived maps of various types, if required (e.g. combination of single-element coloured maps with superimposed points representing element contents or ratios, etc.)

Examples of the above basic types of graphic presentation are shown on Figs 1, 2, 3.

Another type of output in the Geochemical Atlas of Groundwater are association geochemical-ecological maps on the scale 1 : 200 000. In these maps anomalies of hydrogeochemically and ecologically important elements including toxic metals will be presented in additive form.

The basis (standard value) are concentration limits from the drinking-water standard and "B" values of water pollution indicators and normatives.

With the aim of obtaining a more complex information on natural waters in Slovakia, some further

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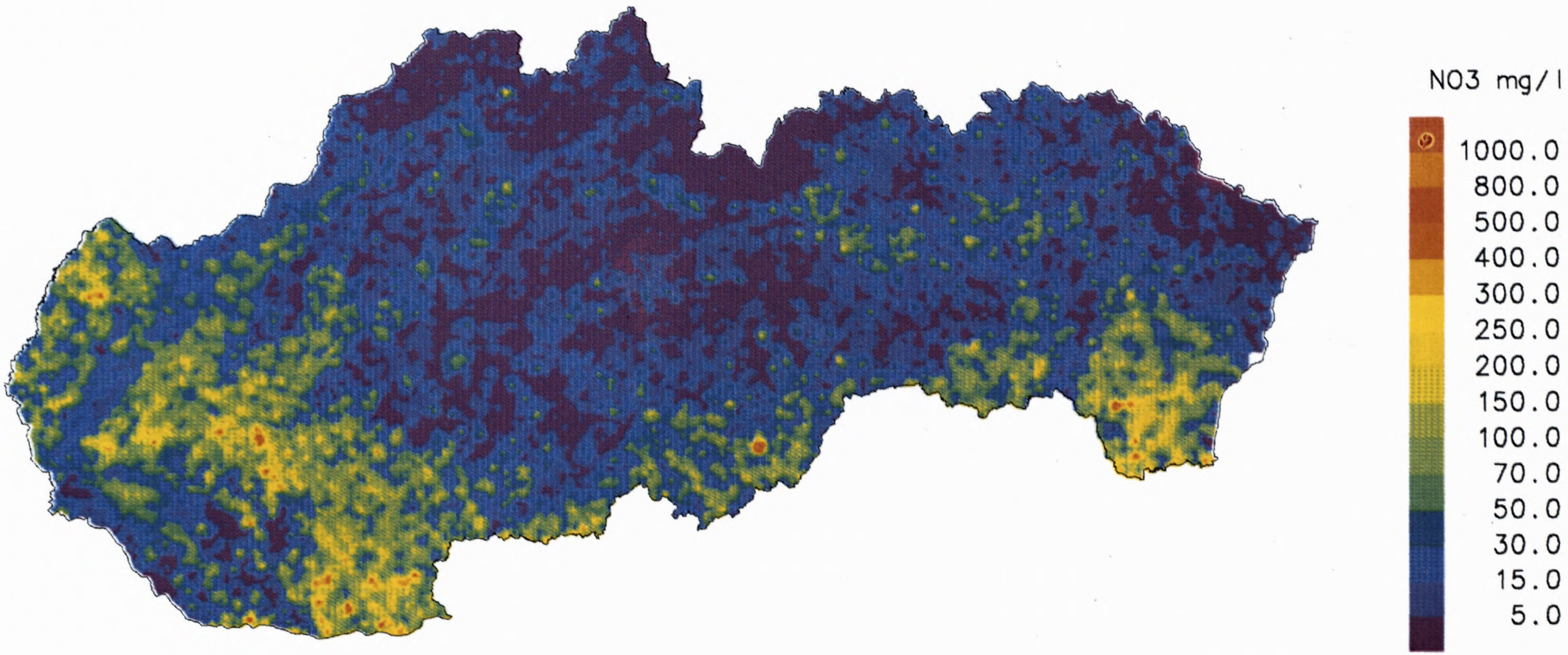
The Geochemical Atlas of Slovakia, Groundwater

SCALE 1:2 000 000, number of samples: 16 392



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The Geochemical Atlas of Slovakia, Groundwater

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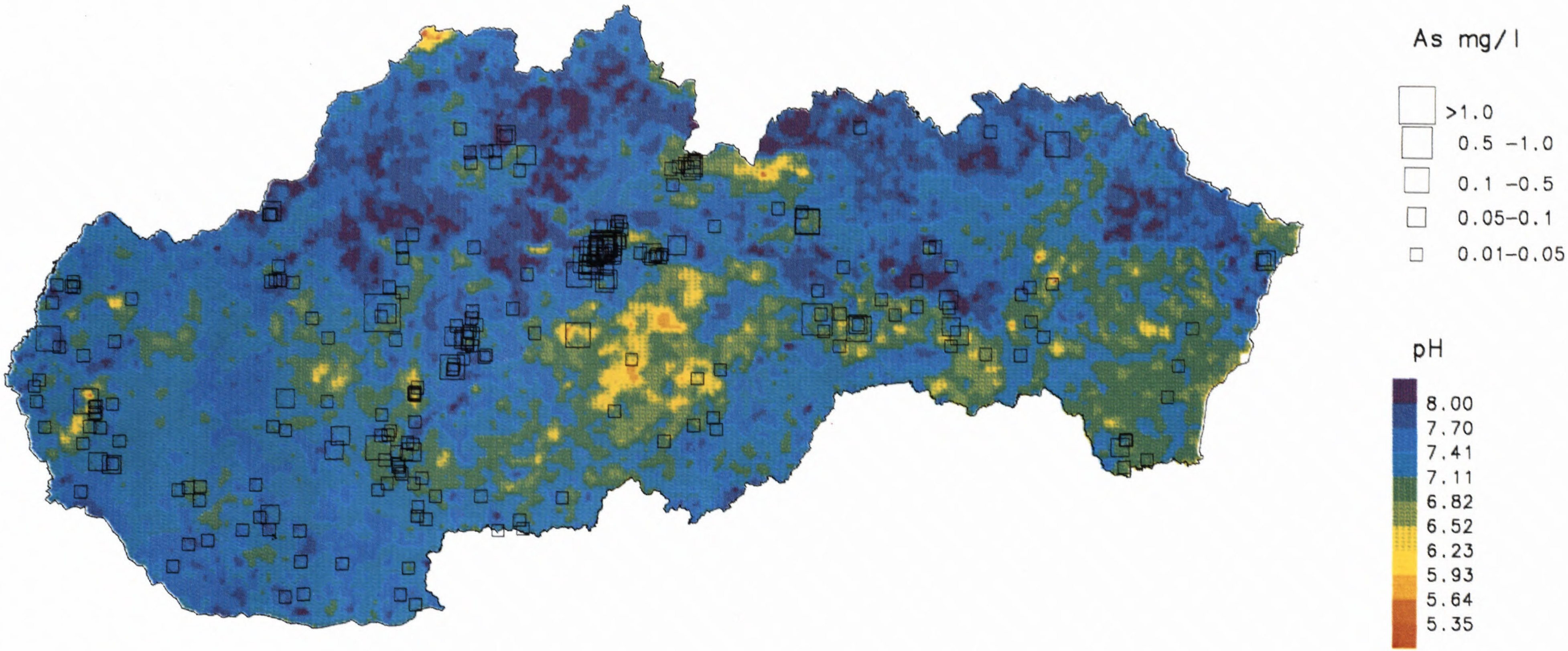

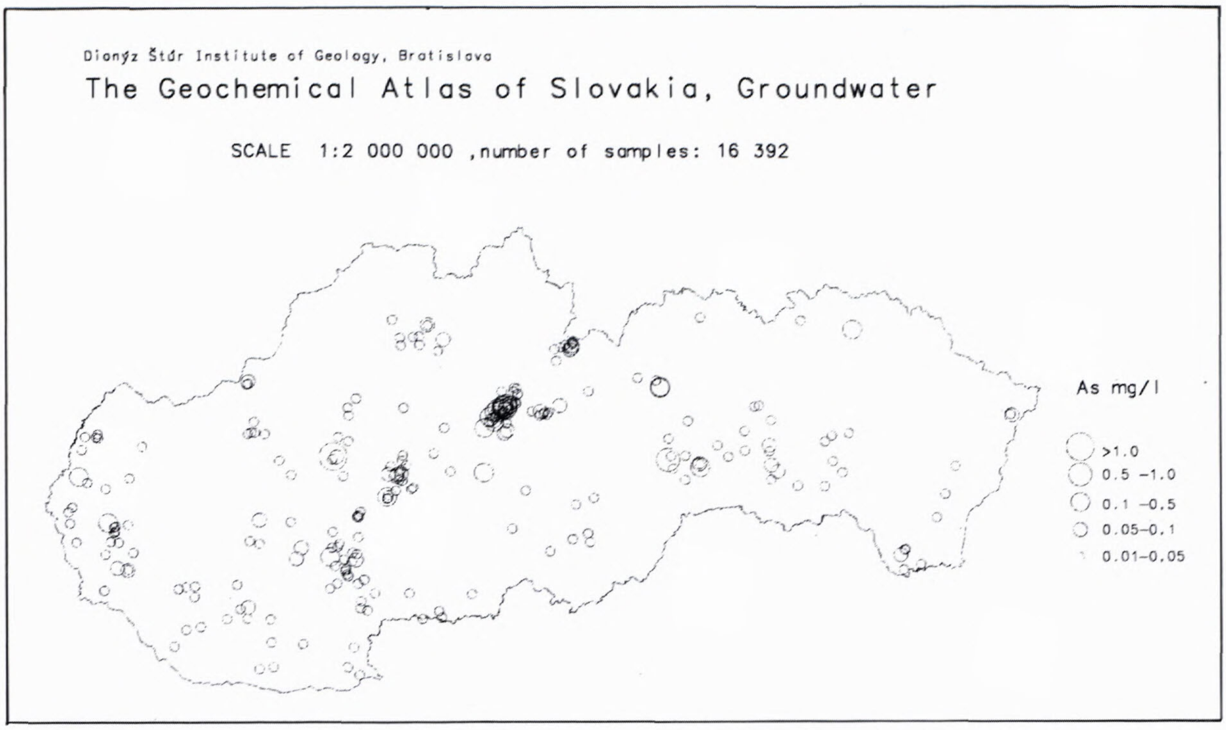

characteristics of natural water in Slovakia will be described and presented in the Geochemical Atlas in the form of additional maps, e.g. chemical composition of winter precipitation (snow) and natural radioactivity of groundwater (Rn^{222}, Ra^{226} and U^{238}).

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Geothermal energy of Slovakia

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Abstract. The geologic setting of Slovakia is favourable for the occurrence of geothermal - energy sources to the south of the Klippen Belt, i. e. in the Inner Western Carpathians. 26 areas or structures with geothermal waters have been outlined in this zone. Temperatures at a depth of 1000 m average 46 °C (ranging from 20–72 °C) and at 2000 m 87 °C (46–120 °C). The mean value of heat flow density is 81.8 ± 20.6 mW/m^2. The total thermal – energy potential of geothermal waters in all prospective areas amounts to 6608 MWt. Geothermal waters are used for space heating, recreation and swimming pools in 35 localities. Their combined discharge is 601 l/s and recoverable thermal power 83 MWt.

Key words: hydrogeothermal conditions, geothermal areas, geothermal waters, boreholes, geothermal - energy potential

Fig. 1, Table 2

The Western Carpathians, which occupy the territory of Slovakia, consist of an Alpine folded mountain system and Tertiary basins. The mountain system is divided lengthwise by the Klippen Belt into the Outer (Flysh Belt – Paleogene sediments) and Inner Western Carpathians. The Inner Western Carpathians are characterized by abundant pre-Upper Carboniferous crystalline schists, Variscan granitoids, Late Paleozoic sediments and volcanics, largely carbonate Mesozoic, pre-Senonian nappe structure, Alpine metamorphism, formation of granitoids, post-Cretaceous vertical movements which modified basins of deposition, and tectonics which gave rise to morphostructural elevations (mountains) and depressions (basins) with widespread post-nappe Paleogene and Neogene sedimentary and volcanic formations.

The geologic setting is favourable for the occurrence of geothermal energy sources only to the south of the Klippen Belt, i.e. in the Inner Western Carpathians. 26 areas or structures with geothermal energy have been distinguished in this zone. These include mostly Tertiary basins and intramontane depressions, namely Komárno high block (1), Danube Basin central depression (2), Bánovce Basin (Topoľčany bay – 3), Trnava bay (4), Piešťany bay (5), NW tract of the Central Slovakian Neovolcanics (6), SE tract of the Central Slovakian Neovolcanics (7), Upper Nitra Basin (8), Turiec Basin (9), Žilina Basin (10), Skorušina Mts. (11), Liptov Basin (12), W and S expases of Levoča Basin (13), Upper Strháre – Trenč graben (14), Rimava Basin (15), Trenčín Basin (16), Ilava Basin (17), Levice block (18), Komárno marginal block (19), Vienna Basin (20), Zlaté Moravce bay (21), NE tract of Levoča Basin (22), Humenné Ridge (23), Košice Basin (24), structure Beša- Čičarovce (25) and Dubník depression – 26 (Fig. 1). The combined area of the 26 hydrogeothermal areas or structures covers more than a quarter (27 %) of Slovak territory. Geothermal waters in the hydrogeothermal areas or structures are largely associated with Triassic dolomites and limestones of the Krížna and Choč nappes (Fatricum and Hronicum), less frequently Neogene sands, sandstones and conglomerates (Danube Basin central depression, Horné Strháre – Trenč graben, Dubník depression) and Neogene andesites and related pyroclastics (structure Beša – Čičarovce). These rocks – geothermal aquifers occur at depths 200–5000 m (outside spring areas) and contain geothermal waters 20–240 °C hot.

The temperature pattern in Slovakia is known fairly well. 376 temperature sections based on deep drilling have been compiled. They represent all major structural-tectonic units of the Western Carpathians. Both the vertical and areal distribution of temperatures indicates major differences between individual units and great variability of the thermal field in Slovakia. Temperatures at a depth of 1000

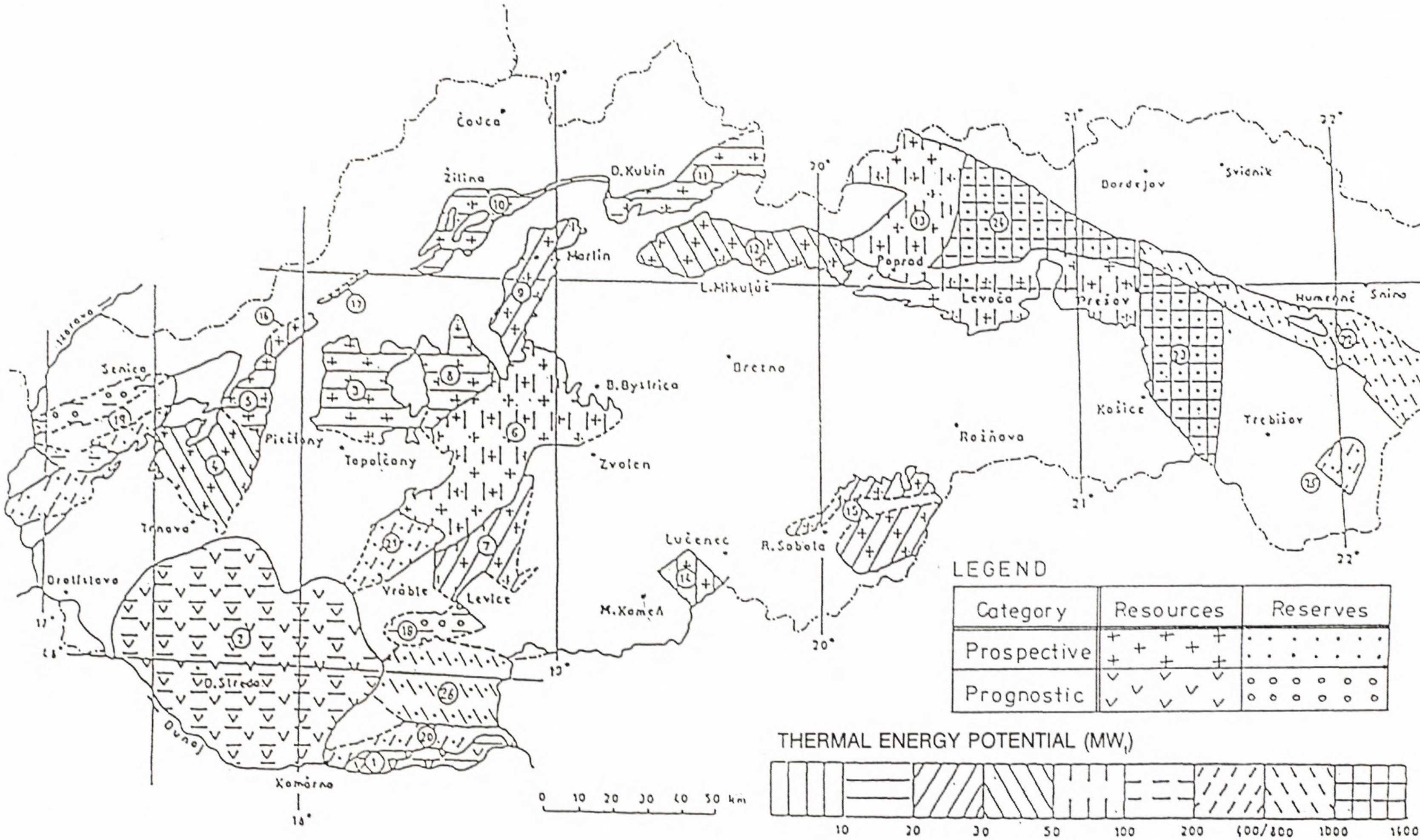

Fig. 1 Map of prospective geothermal water areas or structures in Slovakia and their thermal energy potential (REMŠÍK and FENDEK, 1994)
1 – Komárno high block, 2 – Central depression of the Danube Basin, 3 – Bánovce Basin, 4– Trnava bay, 5 – Piešťany Bay, 6 – Central Sllovakian neovolcanics (NW part), 7 – Central Slovakian neovolcanics (SE part), 8 – Upper Nitra basin, 9 – Turiec basin, 10 – Žilina basin, 11 – Skorušina Mts., 12 – Liptov basin, 13 – Levoča basin (Wand S part), 14 – Horné Strháre-Trenč graben, 15 – Rimava basin, 16 – Trenčín basin,, 17 – Ilava Basin, 18 – Levice block, 19 – Vienna basin,

m average 46 °C (ranging from 20 to 72 °C) and at 2000 m 87 °C (46–120 °C). The mean thermal gradient in the depth interval 0–2000 m in major Western Carpathians units varies from 23.5 to 46.0 °C/km.

The lowest mean temperatures at 1000 m (below 30 °C) and at 2000 m (below 50 °C) have been recorded in the central sector of the Inner Western Carpathians. On the other hand, the highest temperatures typically occur in the southern tract of the Central Slovakian Neovolcanics and Eastern Slovakian Neogene Basin which is a part of the Pannonian Basin. Temperatures here at a depth of 1000 m exceed 70 °C and at 2000 m attain 100 – 120 °C. In the Western Carpathians intramontane basins there is a multitude of local low- as well as high-temperature anomalies caused by convective heat transfer by waters circulating in subsurface reservoirs which reflect hydrogeologic conditions in these structures.

Temperature patterns allow to divide the Western Carpathians into two parts which differ from one another in geothermic activity and spatial distribution of the earth's heat. Fairly low temperatures are characteristic of core mountains in the central and northern sectors of the Inner Western Carpathians and of the western tract of the Outer Flysh Belt. In contrast, high subsurface temperatures typically occur in Neogene basins and volcanic mountains with adjacent intramontane basins. Thermal activity generally decreases from the inner to outer tectonic units.

Heat flow density has so far been measured in 137 boreholes throughout Slovakia. The mean value calculated as an arithmetic mean of all data is 81.8 ± 20.6 mW/m^2 and the same value adjusted to paleoclimatic conditions amounts to 84.4 ± 20.2 mW/m^2. Heat flow densities in the Western Carpathians are highly variable, and regionally fall from the inner structures towards the outer Carpathian arc.

The highest heat flow density (over 100 mW/m^2) has been recorded in the Eastern Slovakian Neogene Basin. Heat flow density distribution reflects the deep structure, thinned earth's crust in this area and increased heat transfer from the upper mantle. High heat flow density values (80–110 mW/m^2) are also typical in the Central Slovakian Neovolcanics. Increased geothermic activity here is directly related to extensive Neogene volcanism, while increased transfers from the upper mantle play only a minor role. Heat flow densities over 90 mW/m^2 have been calculated in the central and eastern Danube Basin (within the proximity of the neovolcanics). Heat flow densities in the Western Carpathians core amount to 50–60 mW/m^2.The Central-Carpathian Paleogene typically displays 65–75 mW/m^2 and the Outer Flysh Belt around 70 mW/m^2. Very low heat flow densities (50–55 mW/m^2) have been noted in the Vienna Basin.

Maximum differences between mean surface heat flow densities in major structural-tectonic units of the Western Carpathians attain as much as 55 mW/m^2. They result from different deep structures and dynamics of basic neotectonic blocks. High heat flow densities occur in areas of Miocene volcanism and thinned crust, whereas low heat flow densities typically occur in areas underlain by a thick crust.

As far as temperature is concerned, geothermal waters in Slovakia (Table 1) are dominated by low-temperature ones ($T < 100$ °C) while medium-temperature sources ($T = 100$–150 °C) are rarer and high-temperatures ($T > 150$ °C) are least frequent.

Research, prospecting and exploration of geothermal waters has so far been carried out in 13 prospective areas in Slovakia (Fig. 1 – areas 1, 2, 3, 8, 9, 11, 12, 13, 18, 19, 20, 21, 26) and in one unprospective area (southern part of the Eastern Slovakian basin – a unsuccessful well).

In 1971–1994 (Table 2) a total of 61 geothermal wells were drilled (only 4 of them were unsuccessful) which verified 900 l/s of waters whose temperature varies from 20 to 92 °C. Thermal capacity of these geothermal waters amounts to some 184 MWt (water temperature will be reduced to 15 °C during exploitation). Geothermal waters were captured by wells 210 to 2605 m deep, and their free outflow mostly ranged from 5 to 40 l/s (Remšík, 1993). Chemically, the waters are represented by Na-HCO3-Cl, Ca-Mg-HCO3-SO4 and Na-Cl types, their T.D.S. is 0.7–20.0 g/l.

In the other 13 prospective areas, geothermal waters have not been verified by wells (Fig. 1 – areas 4, 5, 6, 7, 10, 14, 15, 16, 17, 22, 23, 24, 25), but seven of them (Fig. 1 – areas 4, 5, 10, 16, 17, 21, 23) have been geologically assessed for the purpose of prospecting and exploration for geo-thermal waters. The evaluation of these areas, based on earlier geological information, results of oil wells and geophysical measurements, allowed us to propose wells for geothermal waters in the individual areas.

The evaluation of the thermal-energy potential (TEP) of geothermal waters in Slovakia's individual prospective areas is given in Fig. 1. The total TEP

Table 1 Distribution of low- to high-temperature geothermal waters (Remžík and Fendek 1994)

Type and temperature of geothermal waters	Defined geothermal water structures or areas	Number of geothermal water structures and areas
Low-temperature T < 100 °C	Komárno high block, Central depression of the Danube basin, Bánovce basin, Trnava bay, Piešťany bay, Central Slovakian neovolcanics (NW part), Central Slovakian neovolcanics (SE part), Upper Nitra basin, Turiec basin, Žilina basin, Skorušina Mts., Liptov basin, Levoča basin (W + S part), Horné Strháre – Trenč graben, Rimava basin, Trenčín basin, Ilava basin, Levice block, Komárno marginal block, Vienna basin, Komjatice depression, Levoča basin (N part), Humenský chrbát Mts., Košice basin, Beša – Čičarovce structure, Dubník depression	26
Medium-temperature T = 100 - 150 °C	Beša-Čičarovce structure, Central depression of the Danube basin, Košice basin, Humenský chrbát Mts., Levoča basin (N part), Liptov basin, Turiec basin, Central Slovakian neovolcanics (NW part), Bánovce basin, Žilina basin, Ilava basin, Trenčín basin, Piešťany bay, Trnava bay, Vienna basin, Komárno marginal block	16
High-temperature T > 150 °C	Beša-Čičarovce structure, Žiar basin (part of Central Slovakian neovolcanics – NW part), Košice basin, Vienna basin, Central depression of the Danube basin	5

of geothermal waters in all prospective areas amounts to 6608 MWt (FENDEK, 1993), of which the nonrenewable thermal-energy potential of geothermal water reserves accounts for 6008 MWt and renewable thermal-energy potential of geothermal water resources for 600 MWt.

Geothermal waters (apart from thermal mineral waters used for medical purposes in spas) in Slovakia are an auxiliary energy source. Given the lack of energy, rising energy prices, necessity to protect the environment – mainly the atmosphere – geothermal energy may be successfully and effectively exploited as an available local source of heat or even electricity.

Hydrogeothermal investigations have revealed that Slovakia is particularly rich in low- temperature geothermal resources (water temperatures below 100 °C). The extent and technology of geothermal-energy exploitation are inadequate. Recovery rate of the currently exploited geothermal resources is only about 20 %.

Geothermal waters are used for space heating, recreation and swimming pools in 35 localities. Their combined discharge is 601 l/s and recoverable thermal power 83 MWt. Buildings in three towns are partly heated in this way, and so are greenhouses covering 20 hectares in ten localities. About 80 thermal pools whose total area exceeds 50 000 m^2 serve for swimming and recreation. Thermal spas and swimming pools can admit 75 000 visitors a day. The majority of exploited sources of geothermal energy are situated in southern Slovakia (Danube Basin), primarily in the Danube Basin central depression. At Vrbov in the Vysoké Tatry area, geothermal water is used not only for recreation but also for fish farming. In the Liptov Basin, geothermal water is used for recreational swimming in one thermal spa (Bešeňová).

Essential preconditions to geothermal-energy exploitation have already been created in Slovakia. A project to heat 1300 flats, a city hospital and a pensioners hostel in the town of Galanta in the Danube Basin is under preparation. Another project is the construction of a reinjection station at Podhájska (to heat greenhouses and houses through thermopumps and swimming pools). Geothermal water will also be used to heat 500 flats and an indoor swimming pool in the town of Poprad (Vysoké Tatry area).

Approximately 800 MWt of geothermal resources will presumably be exploited by 2005. At 45 % recovery rate they yield 360 MWt of thermal power which in turn corresponds to 2160 GWh of

Table 2 Results of geothermal wells drilled in 1971–1994 in Slovakia (REMŠÍK and FENDEK, 1994)

Structure area	Number of geothermal wells	Drilling period	Aquifers	Depth of perforated intervals (m)	Discharge (l/s)	Water temperature (°C)	Heat power (MW_t)	T. D. S. (g/l)	Chemical type of waters (over 20 eq. % of 100 % ion sum total)
Komárno block	6	1972–1990	Triassic dolomites, limestones, Neogene sands, conglomerates	77–1761	5.5–70.0	20.0–56.0	0.12–7.33	0.7–90.0	Ca-Mg-HCO_3-SO_4 Na-Cl mixed type
Central depression	34	1971–1990	Neogene sands, sand-stones, conglomerates	276–2487	0.3–25.0	23.0–91.5	0.13–6.80	0.5–8.3	Na-HCO_3 Na-HCO_3-Cl Na-Cl
Dubník depression	2	1989–1990	Badenian sandstones, conglomerates	745–1905	1.5–15.0*	52.0–75.0	0.25–2.40	10.0–30.0	Na-Cl Na-SO_4-Cl
Levice block	2	1973–1986	Badenian clastics, Triassic dolomites	995–1740	28.0–53.0	69.0–80.0	6.30–14.42	19.2–19.6	Na-Cl
Komjatice depression	1	1989	Pannonian sands, sandstones	1509–1700	12.0	78.0	2.50	20.1	Na-Ca-Cl-HCO_3
Bánovce basin	2	1984–1985	Triassic dolomites	1512–2025	2.0–17,0*	40.0–55.0	0.33–1.78	0.7–6.0	Na-HCO_3-SO_4 Ca-Mg-HCO_3
Vienna basin	2	1982–1984	Triassic dolomites, limestones	1242–2570	12.0–25.0	73.0–78.0	2.91–6.59	6.8–10.9	Na-Ca-Cl-SO_4 Na-Cl
Upper Nitra basin	1	1979–1980	Triassic limestones, dolomites	1677–1851	26.0	66.0	4.85	0.93	Ca-Na-Mg-HCO_3-SO_4
Liptov basin	4	1976–1991	Triassic dolomites, limestones	1315–2486	6.0-31.0	32.0–62.0	0.43–5.89	0.5–4.8	Ca-Mg-HCO_3-SO_4 Ca-Mg-HCO_3
Levoca basin	3	1981–1994	Triassic dolomites	835–1983	20.0-33.0	46.0–59.0	2.58–6.08	3.0–4.0	Ca-Mg-HCO_3-SO_4
Skorusina Mts.	1	1990–1991	Triassic dolomites	950–1565	100.0	54.0	16.3	1.2	Ca-Mg-HCO_3-SO_4
Turiec basin	1	1989–1990	-	2461**	-	-	-	-	-
Ilava basin	1	1989–1990	-	1761**	-	-	-	-	-
Eastern Slovakian basin	1	1973	-	1001**	-	-	-	-	-

* pumping discharge; ** well depth

energy. Geothermal energy will be used for space heating, greenhouses, water for households, for drying, fish farming and for recreational as well as balneologic facilities. It can even be harnessed to generate electricity in the Košice Basin.

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Chemical Time Bombs – Proposed Method for the Map Presentation

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Abstract

The presented paper is a proposal for the method of map presentation of chemical time bombs (CTB), which has been designed for a model region with an area of 1000 sqkm, in the central part of Slovak Republic. The CTB map has been compiled on the basis of a re-evaluation of present state of stream sediments, surface- and groundwaters contamination as well as of the inventary and evaluation of principal sources of polution - waste deposits directly or potentially affecting the environment. The presented method of CTB map represents a model of map presentation of areal and hot-spot CTB with categorisation of their toxicity level and the possibility (probability) of environmental polution.

Key words: stream sediments, surface water, groundwater, waste deposits, chemical time bombs

4 Figs

Introduction

The contamination of the environment with chemicals of various origin and varying composition is at present a very important environmental problem, which has to be dealt with by all economically developed countries. A great danger is the accumulation of chemicals, the so-called chemical time bombs, with possible time-delayed, but sudden effects of long-time accumulate pollutants, due to an accident, natural disaster or slow and permanent changens in the environment, e.g. acid deposition, global climate changes, drainage regime etc.

Within the complex environmental-geochemical research in the Slovak Republic, the project "Long-term environmental risks for soils, sediments and waters in the Danube river basin" has been launched in the year 1991 within the National Environmental Care Program. This project is a part of the international program "Chemical Time Bombs – CTB" , which has been initiated by the Foundation for Ecodevelopment, Mondial Alternatief - VROM NL.

As a part of this project in the Slovak Republic, the Dionýz Štúr Institute of Geology has been given the task of elaborating a method for compiling survey maps of CTB and compiling a model CTB map on the scale 1:50 000 of an area of approximately 1000 sqkm.

As model territory, where the method for CTB map compilation has been elaborated, was selected the area of Žilina and Martin basins, approximately the half of which consists of mountaineous regions (maximum height 1700 m above sea level) and other half of intermontane basins, with intesive economic activiteis and considerable level of antropogenic polution. The natural conditions - the character of rocks and hydrogeological characterization of the territory - are evident in the legend to the map presented on Fig. 1 and 2.

For the compilation of a survey map, criteria for determination and evaluation of potential places of chemical bomb occurrences (hot spots) have been elaborated, as well as their categorisation according to the level of danger to the water component of the environment.

For the compilation of the survey map itself, the following input data have been processed and evaluated according to the elaborated criteria:

– present state of the chemical composition of active stream sediments and their relationship to existing natural and antropogenic sources of contamination

– present state of qualitative properties of underground and surface waters and their relationship to sources of polution

– evaluation of hydrogeological conditions of the studied territory and their classification from the viewpoint of CTB

– inventory of principal sources of polution - waste deposits, with direct or potential evironmental impact.

The proposed method of a survey CTB map represents a compilation of the above input information in a map of areal and spot potential occurrences of chemical time bombs, which may gradually or suddenly decrease the qualitative characteristics of natural water. All input data from chemical analyses represent toxic anorgaic elements and components. Neither soils, nor organic substances have been evaluated, since no complete databases synthesising the studied territory as a whole are hitherto available.

Criteria for potential CTB

The following basic conditions have to be taken into consideration when solving the problem of potential CTB criteria (STIGLIANI et al., 1991):
- gravity of the effects
- non-synchronality of the polution and manifestations of negative effects
- suddeness of the manifestations of negative effects
- discontinuous and non-linear character of the effects

Chemical time bombs represent a time delay (slow, immediate) between the accumulation of toxic matter and its harmful effect (it is not necesarily immediate) after release.

Environmental conditions always have dominant effects. The identification of critical CTB places is represented by high input of toxic components into environment, due to geographic conditions, initiated by sudden change of environmental conditions. In case when the toxic matter is of natural origin, the "hot spots" are relatively difficult to identify.

The following criteria have been determined for the "Survey Map of CTB":

a) toxic element contents in active stream sediment, the concentrations of which in the model region exceed the value of x + 3s, or they exceed the "B" value according to Netherland Standards. These anomalies represent on one hand an areal source of the contaminant, and, on the other hand, from the geographic position of anomalies in natural conditions and the presence or absence of antropogenic polution sources may indicate a primary or secondary source of toxic matter.

b) selected groups of components in ground- and surface water, the contents of which exceed the criteria of STN 75 7111 (Slovak Technical Standard - Drinking water) in the case of groundwater and STN 75 7221 (Classification of surface water quality) in the case of surface water. The distinguished anomalies of contaminated collectors are considered to be an areal CTB, from which gradually, or suddenly, after a change of natural conditions, e.g. a flood wave, change of the infiltration function of the surface flow into drainage and vice versa, the CTB may "explode".

c) hydrogeological characterization of the rock environment:
- type of aquifer permeability
- grade of aquification
- flow direction of groundwater, represents a very important criterion, by which the possibility and velocity of the spread of polutants after a CTB explosion may be evaluated

d) inventory and evaluation of antropogenic polutions sources - waste deposits. At this criterion we were guided by the condition, that CTB is represented by a solid waste accumulation, its toxicity level and the possiblity of contamination. Of course, it is a certain simplification, liquid and gaseous contamination sources were not taken into consideration, however, their impact so far cannot be expressed on a map of this scale, as well as changes of hydrological regime, the effect of which may be a contact of groundwater level with the bottom of the deposit. This may be expressed in the future e.g. by the weight balance method, critical loads etc. This criterion was applied in the identification of hot spots as a numeric code, which was the result of a sum of weighted numeric codes for solid waste deposits in the studied region.

Characterization of evaluated input information

The following input data were available from the studied model region:

1. Map of toxic elements in stream sediments (KANDERA, 1993)

sampling density: 1 sample/1 sqkm
analysed fraction: 0.125 mm
analysed association: 37 elements

The anomalies represent the x + 3s value of element concentration, or exceeding of the "B" value of "Netherland Standards" (BODIŠ, 1993).

2. Natural water quality map (RAPANT, 1993)

sampling density: 1 sample of groudwater/3 sqkm
1 sample of surface water/2 sqkm
analysed association: 35 elements and components
sampling object: groundwater: spring, drillhole, gallery, well (first aquiferous horizon)
surface water: brook, river, water reservoir

On the basis of grouped quality indicators, 8 quality classes of underground water (classes A-H) and 5 classes of surface water (I.-V.) have been defined.

3. Basic hydrogeological characterization of the region

The following parameters of hydrogeological characterization of the rock environment have been applied:

– type of aquifer permeability
– grade of aquification
– areas of surface water inlet (possible sources of contamination) into aquified collectors

The characterization of rock environment and the most important hydrogeological chacteristics of the territory are evident from figures 1 and 2, the legend to the CTB map.

4. Spot sources of pollution

Potential sources of pollution were identified with the help of a database (register) of waste deposits in the studied region. The following data on waste deposits were used for the CTB map construction: localization, type of waste, its quantity, toxicity and possibility of contamination spread.

Methods and legend of CTB map

The philosophy of distinguishing critical CTB places (hot spots) in the model region was based on available information on the abiotic component of the environment and the definition of the term "Chemical Time Bomb". The survey map shows the areal and spot critical places, as well as the grade of danger from the viewpoint of polutant contents and the time factor of contaminating matter spread after "CTB explosion". It is necessary to note that from the viewpoint of the endangerment of biotop and man, there are at present no real data on the speciation of pollutants, i.e. the form of their occurrence in various media. In any case, there has been analysed the total sum of an element or component in natural water and stream sediments.

The compilation of chemical time bombs map was based on the following parameters and data types:

The used data types may be divided into:

a) tables related to points (characteristics of spot anomalies and waste deposits)

b) graphic (anomalous contents of contaminants, hydrogeological characterization)

There are two types of critical CTB locations, areal and spot (Fig. 3).

I. AREAL CRITICAL CTB SITES are identified on the basis of criteria in anomalously increased element or component contents in underground and surface water, active stream sediments and the hydrogeological characteristics of the rock environment. They represent an accumulation of toxic matter in water collector or in stream sediment. In case when above the critical place (anomaly) or in river sediments there is an anomaly in the chemical composition of natural water in the drainage area, where in the whole drainage area above the anomaly or inside it there is no secondary pollution source, these anomalies may be considered as geogenic.

The position of critical places of contaminated water or sediments may be various, e.g. in drainage areas, in the direction of waterflow, the first critical CTB place is the sediment, then the water or vice versa, or they may overlap.

From abovesaid the following combinations result for the identification of potential CTB source:

a) contaminated water
b) contaminated sediment
c) contaminated water as well as sediment

According to contamination grade of natural water and river sediments, areal CTB anomalies have been divided into three categories - low, medium and high.

Areal critical CTB places are thus constructed from "layers" of graphic data on the quality of underground and surface water, the quality of river sediments, in relation to the basic hydrogeological characteristics.

DATA	PARAMETERS	DATA TYPES
hydrogeochemical data	analysis of ground- and surface water	areal anomalies, isolines, spot data
stream sediments	analysis of sediments	areal anomalies, isolines, spot data
hydrogeological data	grade of aquificaton, character of collectors, flow direction	areal and spot data, linear data
land	river network, inhabitated areas, waste deposits	areal data, spot data, linear data

Categorisation of areal CTB

	sediment	ground water	surface water
low	1-element anomaly	quality class C-D	quality class III.
medium	2-element anomaly	quality class E-F	quality class IV.
high	3- and more element anomaly	quality class G-H	quality class V.

II. SPOT CRITICAL CTB SITES – they can be defined as places with an occurrence of waste deposit, characterized by weighted numerical code and the type of rock environment, which may potentially or immediately endanger the environment.

The numerical code includes the following parameters:

– toxicity of deposited waster matter is evaluated according to the origin and charater of the waste in 4 classes:

0 – non-toxic
1 – low-toxic
2 – medium-toxic
3 – high-toxic

– the quantity of waste (in m^3)

1 – up to 1000 m^3
2 – 1000 –10 000 m^3
3 – over 10 000 m^3

– contamination possibility (technical state of the deposit), the evaluation is based on 4 grades:

0 – no
1 – possibly
2 – probably
3 – yes

– the waste deposit is situated in an area of toxic element anomaly in stream sediment:

0 – no anomaly occurrence
1 – one element anomalous
2 – intersection of two element anomalies
3 – intersection of anomalies of 3 and more elements

– the waste deposit is situated in an area of anomaly occurrence in ground water:

0 – no anomaly occurrence
1 – class C-D
2 – class E-F
3 – class G-H

– the waste deposit is situated in an area of anomaly occurrence in surface water:

0 – no anomaly occurrence
1 – class III.
2 – class IV
3 – class V.

The sum of resulting weighted values of numerical codes reached 1-18 and it takes into account practically the categorisation of CTB according to toxicity grade:

1–3 no CTB
4–7 low CTB
8 –10 medium CTB
11–18 high CTB

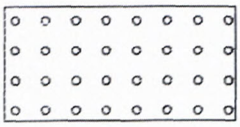
The results of the summing for various waste deposits are shown in the list of selected waste deposits presented in the Appendix. In the map, the criterion is shown as the size of the quadrangle and the numbers shows the localisation of the deposit with a detailed characterization in the database (Appendix).

The categorisation of critical CTB spots according to contamination possibility takes into account also the time factor of contaminated matter spread at slow or immediate release (explosion). This factor is shown by the intensity of colour inside the quadrangles. The categorisation (low, medium , high) has been made according to the aquification grade of the territory (transmissivity coefficient for collectors with inter-granular permeability, specific run-off for other collectors).

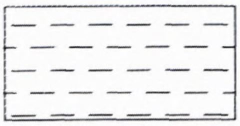
categorisation of spot CTB according to contamination possibility	aquification grade
high medium low	very high, high medium low

DESCRIPTION OF ROCK ENVIRONMENT

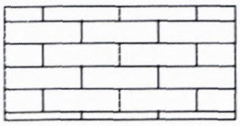
I. Type of permeability of aquifers



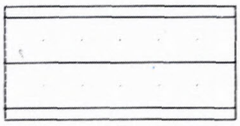
Intergranulal permeability (Q – sands, gravels; N – sands, gravels).



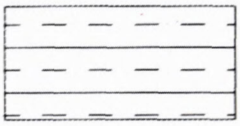
Fissure permeability (granitoids, crystalline schists, dolomites, quartzites, sandstones).



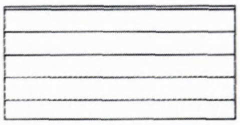
Karstic–Fissure permeability (limestones, dol. limestones, alternating limestones and dolomites).



Irregular alternation of aquicludes and intergranular aquifers (N – alternation of clay, sands, alternation of marls with sands).



Irregular alternation of aquicludes and fissure aquifers (Fg, N, Mz – alternation of sandstones with claystones).



Aquiclude area impermeable as a whole (N – clays, marls, Pg – claystones, claystones predominating over sandstones, K – marls, marly limestones, T – Carpath. keuper, Lunzs beds, shales, shales predominating over sandstones).

II. Degree of water–bearing in aquifers

(expressed by a number next to age symbol of aquifer)

WATER–BEARING		Aquifers with intergranular permeability, T ($m^2 . s^{-1}$)	Other aquifers Q ($l . s^{-1} . km^{-2}$)
1	very high	$> 1.10^{-3}$	> 13
2	high	$1.10^{-4} - 1.10^{-3}$	9 – 13
3	medium	$1.10^{-5} - 1.10^{-4}$	3 – 9
4	low	$< 1.10^{-5}$	< 3
5	area without aquifers		

III. Age of aquifers

Q Quaternary
N Neogene
Pg Paleogene
Mz Mesozoic (generally)
K Cretaceous
T Triassic
γ crystalline rocks (generally)

IV. Other symbols

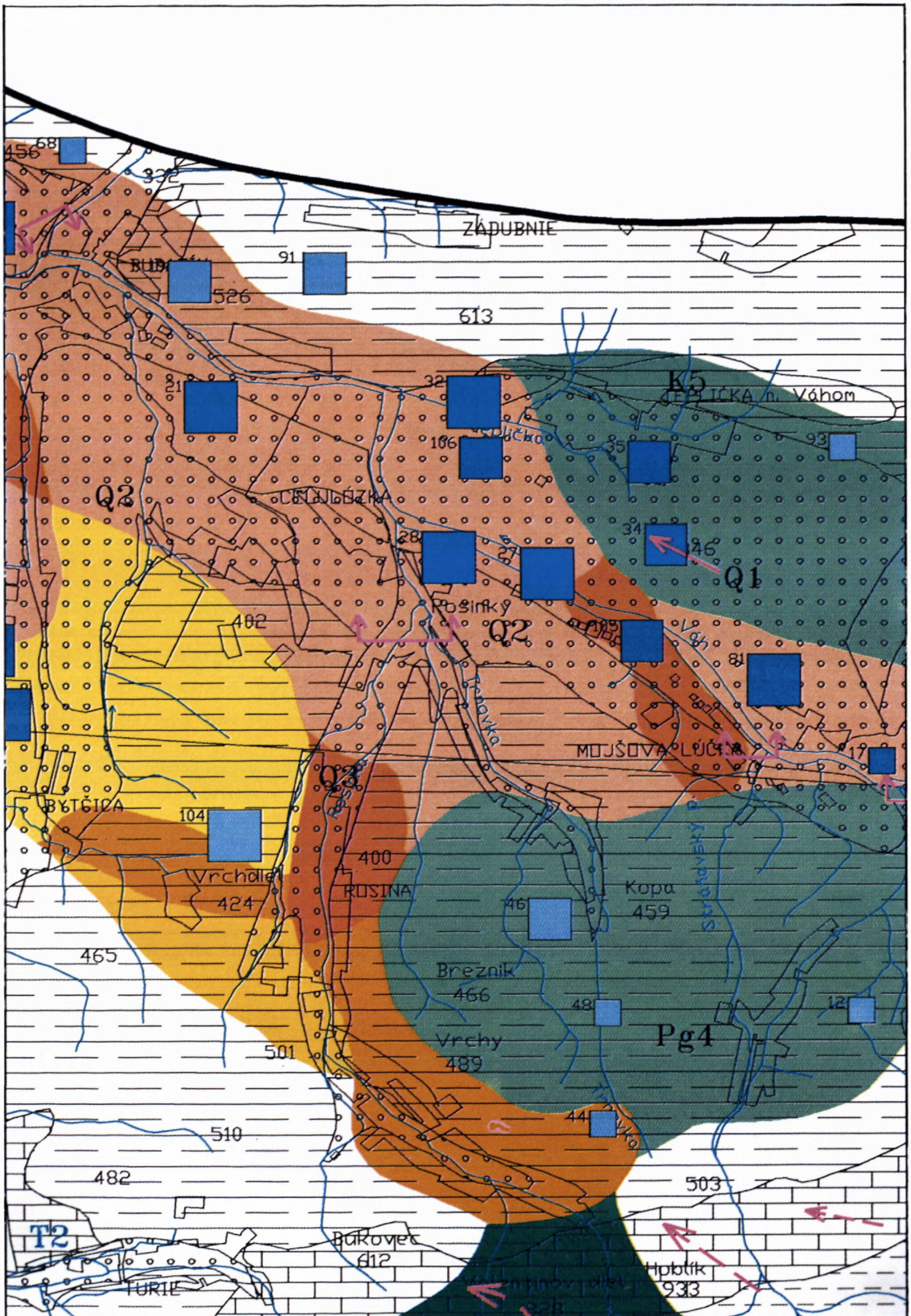
Aquifer boundaries

Direction of grounwater flow (observed, presumed), possible direction of contamination spreading

Section of surface stream with possible entry of contaminated waters

Entries of surface streams into areas of significant aquifers

Significant local losses of surface streams to aquifers


ZÁDUBNIE
613
K5
Váhom
Q2
CELULÓZKA
Q1
Pošinky
Q2
MOJŠOVA LÚČKA
Q3
BYTČICA
Vrchdiel
424
400
RUSINA
Kopa
459
465
Breznik
466
Vrchy
489
Pg4
501
510
482
503
T2
Bukovec
612
Hubtík
933
TURIE

CRITICAL CTB SITES

A. Local

CTB classification according to degree of toxicity	CTB classification according to contamination potentiality
low	low
medium	medium
high	high

B. Areal

CTB classification	Potential CTB source
low	contaminated water
	contaminated sediment
	contaminated both, water and sediment
medium	contaminated water
	contaminated sediment
	contaminated both, water and sediment
high	contaminated water
	contaminated sediment
	contaminated both, water and sediment

Conclusion

The proposed method of CTB survey map compilation represents a possibility for showing CTB "hot spots" on a map, i.e. the accumulation of chemical matter with possible delayed manifestations of the accumulated pollutants due to an accident, catastrophy or due to slow and long-term changes in the environment. On the basis of the accepted philosophy, areal and spot CTB sources are distinguished, which are the evaluated and categorised on the basis of the character and origin of contaminants, their toxicity and the probability of contamination spread into natural environment.

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Mapping Critical Loads/ Exceedances: Natural Waters of Slovakia

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Abstract:

Acidification of natural water due to acid precipitation is an environmental problem affecting large areas of Europe and eastern regions of Northern America. Acidification is causing ecological changes of natural environment and fish mortality. Within the contract on environmental co-operation between Norway and Slovakia, this contribution presents results of the pilot stage of the project "Mapping critical levels/loads for Slovakia", realised in the central part of Slovakia (map sheet 1 : 200 000 Banská Bystrica), in a 10 x 10 km grid. Critical loads were calculated from the present chemical composition of surface and groundwater with the help of steady-state model (SSWC). Critical loads of acidity for surface water were systematically higher than those for groundwater. Acidity values have not been exceeded in surface, neither in groundwater in any of the cells.

Key words: critical loads/exceedances, surface water streams, groundwater, steady-state model

5 figs.

1. Introduction

Solving of the problems of impact of acid deposition on different components of natural environment is a serious scientific as well as political interest in many countries of Europe and Northern America. The most important for the evaluation of the effects of strong acids from atmospheric deposition on natural water, forests, soils, the condition of biotop, human health and various materials (cultural monuments etc.) is the determination and definition of limits for the deposition of acid components. These limits or critical loads are defined as "highest depositions of acid components causing no changes leading to long-term harmful effects on the structure and function of an ecosystem" (NILSSON-GRENUFELT, 1988). The aim of determining and defining critical loads is to determine the quantity and character of acid component deposition (above all SOx, NOx, organic compounds etc.) in a way that would protect the environment in the future. On the basis of the "Convention on Long-Range Transboundary Air Pollution" (the Geneva convention), "Task Forces for Mapping the Critical Loads and Areas where the Critical Loads are Exceeded" have been formulated. The manual for calculating critical loads and their exceedances for soils as well as surface water, has been elaborated by SVERDRUP et al. (1990). In Scandinavian countries (Finland, Sweden and Norway), critical loads and their exceedances have been calculated on the basis of regional data on chemical composition of surface streams in an EMEP grid (150 x 150 km), divided into 3 and 3 sub-parts (HENRIKSEN et al., 1992).

The Slovak Republic came into existence at the beginning of 1993, after the disintegration of the Czechoslovak Federal Republic. The project of critical loads mapping became stagnant. For this reason, as a part on the Agreement on Environmental Co-operation between Norway and Slovakia, the project "Mapping Critical Levels/Loads for Slovakia" was launched in 1992, with participants from the Norwegian Institute for Water Research (NIVA), the Lund University, the Slovak Hydrometeorological Institute, the Dionýz Štúr Institute of Geology in Bratislava, the Forest Research Institute in Zvolen, the Forestry University in Zvolen and Research Institute for Irrigation in Bratislava.

The realisation of the project started in June 1994. The contribution presents results of mapping of critical loads and their exceedances in natural (ground- and surface) water from a selected pilot region (map sheet 1 : 200 000 Banská Bystrica), representing approximately 20% of the Slovak territory.

Grid size for the construction of critical loads map of Slovakia corresponds to the EMEP grid. The EMEP grid cell of 50x50 was subdivided into 25 cells. This means that the grid distance was approximately 10 km.

Critical acidity loads were calculated on the basis of present chemical composition of ground- and surface water. In the contribution there is presented the method used for the evaluation of critical loads for natural water, while we assumed sulphur was the only acidifying component. We are considering to include in future into the calculations also another important acidifying component - nitrogen.

2. Natural conditions of the pilot territory

The pilot area represents about 20% of the total Slovak territory. It includes the following geographic units: In the northern part, from west to east: Malá Fatra Mts. (highest peak 1574 m a.s.l.) and the Nízke Tatry (Low Tatras) Mts. (highest peak Ďumbier 2043 m a.s.l. - the highest point of the area). In the southern part, from west to east - Štiavnické vrchy Hills (highest peak 1009 m a.s.l.), Kremnické vrchy Mts. (highest peak 1265 m a.s.l.), Javorie (highest peak 1044 m a.s.l.), Poľana (highest peak 1458 m a.s.l.), Veporské vrchy Hills (highest peak 1439 m a.s.l.) and in the south-eastern part the Revúcka pahorkatina Hills (highest peak 602 m a.s.l.). The lowermost location in the south-eastern part of the pilot area is only 200 m high above sea level.

The largest part of this territory belongs to the drainage area of the river Hron. Northern slopes of the Nízke Tatry Mts. are drained by the river Váh and the south-eastern part of the area belongs to the drainage area of the river Ipeľ.

The geological structure of the area under study is composed of practically all most important geological units forming the Western Carpathians. From geological point of view, mountainous areas of this region may be divided as follows:

I. region of core mountain ranges

II. region of Central Slovak Neovolcanics

The lowlands may divided into:

III. intramontane depressions

IV. alluvial deposits or large rivers

I. Core mountain region – the Nízke Tatry Mts., Malá Fatra Mts., Veľká Fatra, Slovenské Rudohorie - are in their central part underlain by various granites, granodiorites and gneisses and, to a lesser extent, by amphibolites. Marginal parts of the above mountain ranges have as their basement Mesozoic, mainly carbonate rocks, lying in cover or nappe position:

– limestones

– dolomites

– marls and marly limestones

II. Central Slovak Neovolcanic region – Štiavnické vrchy and Kremnické vrchy Hills are composed of differed varieties of neovolcanic rocks, mainly andesites, rhyolites and their tuffs.

III. Intramontane depressions - underlain mostly by Tertiary sediments - gravels, sands, clays, sandstones and claystones.

IV. Alluvial deposits of large rivers - the rivers Váh and Hron and their tributaries are underlain predominantly by gravels and sands.

All grids are fully or partially covered with forests. There are three main forest areas (spruce, beech and oak) on the pilot territory.

3. Data used for map construction

An important part of the project was the selection of data, constituting the input into the calculation scheme, as well as their adjustment. The representing and information capacity of thus obtained values is at the same time indicative of the quality of existing databases at SHMÚ and GÚDŠ.

3.1 Atmospheric precipitation, deposition and hydrogeologic conditions

The distribution of atmospheric precipitation and hydrologic characteristics on the pilot area is considerably affected by its extraordinary variability. Average altitudes a.s.l. of the gird cells occur in the range of 250 m in the south-eastern part of the pilot area up to 2043 m in the cell crossed by the crest of Nízke Tatry Mts. Altitude differences in the grid cells often exceed 500 m, in some cases even 1000m. We must bear this in mind when interpreting all average values related to the cells.

Average total annual precipitation in the grid cells have been determined from isohyet map of 30 annual precipitation (1961–1990). This map has been elaborated by the department of climatology at Slovak Hydrometeorological Institute (SHMÚ), on the basis of results obtained from measurements at 116 precipitation stations. The density of the precipitation-measuring network is irregular and decreases with increasing altitude above sea level. It is necessary to stress that the measurement of precipitation in mountain drainage areas, especially in winter, are loaded with a systematic negative error, which in the crest areas of the Nízke Tatry Mts. can exceed 40% of the listed value. The magnitude of the error is a function of the degree of exposure of the station, its determination is difficult and it is possible only by special measurements. Data of precipitation stations are thus presented without correction. In medium-high locations (600–1200 m) the magnitude of the correction in exposed sites is 25-30%, at protected locations it is less than 20%.

Average annual total precipitation on the pilot territory were the lowest (500-650 mm) in its south-eastern part and the highest (1400-1500 mm) on the crest of the Nízke Tatry Mts.

The concentration of sulphates in precipitation water on the whole Slovak territory is a relatively conservative characteristic. Its low horizontal gradient is directed from the north-west to the south-east of the country. Average annual concentration of sulphates in precipitation water in the studied territory in the last five years (1989–1993) was 1.8 mg S/l. In comparison with the first half of the eighties, the present concentration is by about 30% lower, which is consistent with the European decrease of sulphur dioxide emissions.

The bulk deposition of sulphur consists of three components: wet, dry and hidden. The wet deposition may be determined relatively simply on the basis of the results of chemical analysis of precipitation as the product of concentration in precipitation water and total precipitation. Wet deposition of sulphur increases with altitude. Average wet deposition of sulphur in the grid cells in the relevant period varies within the range of 0.6 to 1.8 keq/ha/year.

Average annual SO_2 concentration on the crest of the Nízke Tatry Mts. was in the last years 4–5 $\mu g.m^{-3}$. In valleys (outside cities) they were about three times higher. Assuming an average rate of dry SO_2 deposition of 0.7 cm/s, the dry deposition of sulphur in high mountain levels represents only 10-20% of wet deposition. We may assume a ratio of 1 : 1 for wet and dry deposition in valleys.

Hidden sulphur deposition (capture of water from clouds and fogs on the surface, especially by vegetation) increases with altitude and in higher mountain levels, in relation to their degree of exposure, it may become equal to or even exceed wet deposition. In valleys of the studied territory the contribution of hidden sulphur deposition decreases below 20% of wet deposition.

In view of the absence of measurements of dry and hidden deposition, the bulk deposition of sulphur is estimated in the presented work as twice the wet deposition. This value results from the above considerations and it represents a conservative estimate of the real deposition of sulphur on the pilot territory.

The same factor has been used also in the calculation of total deposition of base cations (Ca, Mg). The uncertainty of this factor is nevertheless considerably higher in comparison with sulphur. Average annual Mg concentrations in precipitation water varied in the range of 0.1-0.3 mg/l, in the case of Ca they were two to three times higher. Total deposition of base cations in equivalent quantities in all cells of the relevant grid represents approximately the half of total sulphur deposition.

Hydrogeologic conditions of the pilot territory are reflecting also its relatively complex geological-geomorphologic setting. From this viewpoint the selected region contains territorial units representing lower regions up to high mountains. A considerable part of the area belongs to a headwater region with sources of good-quality drinking water. The selection of hydrological characteristics was determined by the methodology of the pilot project.

Generally it can be said that the increase of precipitation and decrease of evaporation lead also to increased run-off. Therefore in the Western Carpathians average specific annual run-off increases with altitude and decreases with increasing surface of drainage area. The cells from the viewpoint of preservation of the drainage basin as a natural hydrological unit are not consistent with this. In some cases they contain two or three drainage basins and the determination of sufficiently representative hydrological characteristics is quite difficult.

The derivation of specific run-off was based on isoline map of elementary run-offs and corresponding run-off levels. SHMÚ has these data in its database and isoline maps of elementary run-off are representing the evaluated 50-year data material as basic information for the expertise of this institute. The variability of specific run-off is considerable and its values vary in the range of 2 $l/s.km^2$ (lowlands) up to 45 $l/s.km^2$ (in mountainous regions). Specific run-off for each cell was determined as weighted average from the relevant area and calculated run-off level. This value, given as m^2/year, is another input into the SSWC stationary model and it represents the run-off level for the relevant cell.

Values of run-off level are considerably variable and they are representing the natural condition of each cell. Their values vary in the range of 0.98–0.7 m^3/year for the Nízke Tatry Mts. region, 0.6–0.4 m^3/year for the intramontane region. Lower situated parts, such as the south-eastern part of the map sheet, have values of 0.2–0.09 m^3/year.

3.2 Chemical composition of natural waters

Input data for the chemical composition of groundwater represented a selection from the GÚDŠ database, containing 16 391 chemical analyses from one-specimen sampling of the whole Slovak territory, carried out in the years 1991-1993 with the aim of compiling the Geochemical Atlas of Slovakia - part groundwater. Sampling density was 1 sample/3 km^2. Sampling sites were predominantly springs, shallow drillholes, wells and outflow from mining works, i.e. the collected information shows the distribution of determined components in the first water bearing horizon.

For the calculation of critical loads, average values of selected components have been calculated for the 10x10 km grid cells, from those sampling sites occurring in the relevant grid cell, which was in average 3 sampling sites.

The most frequently represented in the pilot area are groundwaters of $Ca(Mg)-HCO_3$ type, with frequent transition to the $Ca-SO_4$ chemical type. The relatively frequent presence of water of various transitional and mixed types is related to the effects of specific genetic factors (simultaneous effects of several mineralisation factors in the water-bearing aquifer, mixing of waters of various origin etc.) and to locally important effects of anthropogenic factors.

Total dissolved solids of groundwater varies mostly in the range 0.05–1.0 g/l, locally it attains 5 g/l.

The source of base cations (Ca, Mg) are interaction processes water-rock, the most extensively occurring ones in the pilot area being the dissolution of carbonates and ion-exchange processes.

The source of data for the chemical composition of surface stream water were data from the SHMÚ monitoring network and one-specimen sampling carried out by GÚDŠ for the project "Investigation of geological factors of the environment – a perspective programme of Slovak geology" (VRANA, 1992).

Predominant elements in the chemical composition of surface water are calcium and magnesium as products of chemical weathering of rocks, other cations are present in lesser quantities, which is related to the effects of groundwaters and local anthropogenic contamination. From anions, hydrogencarbonates are predominant, but in many cases there are substantially represented also sulphates, due to effects of mine waters, or tectonic dissemination of $Ca-SO_4$ waters from underlying carbonates (sulphate concentrations reach locally 100–500 mg/l). In the upper sections of surface streams is the chemical composition approximately the same.

4. Calculation method

The definition of critical load is the basis for the calculation or estimation of loads with negative effects.

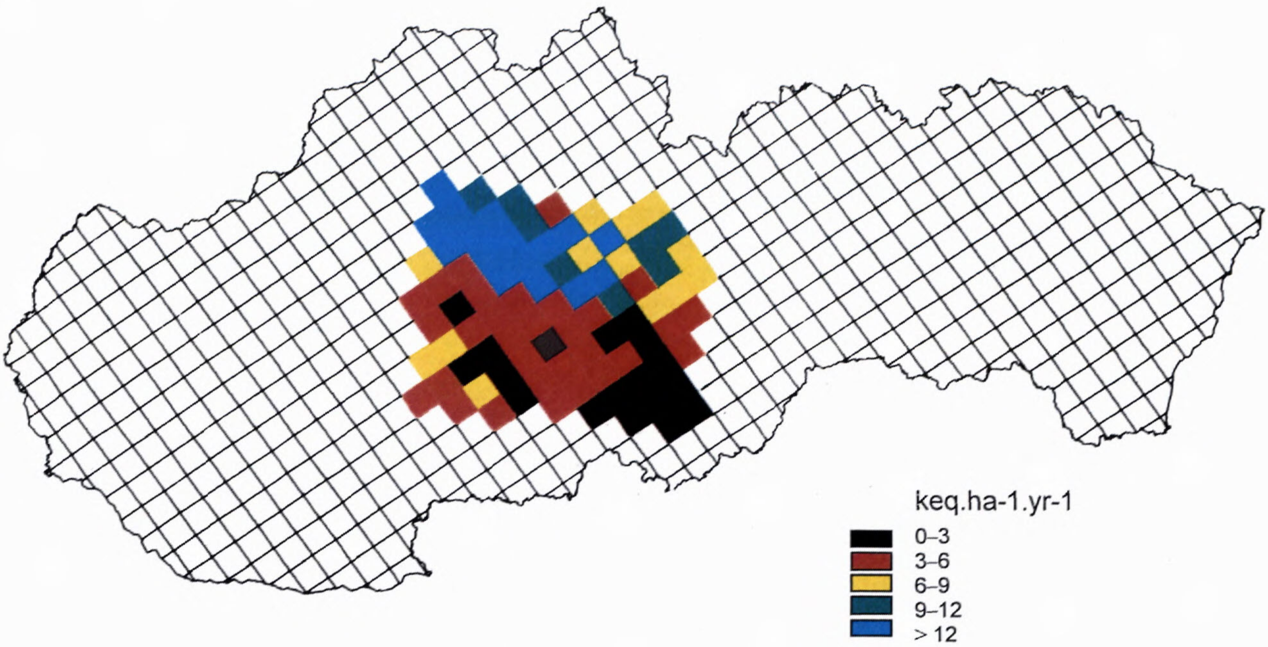
Critical load: the highest load that does not lead to long-term harmful effects on biological systems, such as forest decline or decline and disappearance of fish populations.

Receptor: An ecosystem which may be potentially affected by atmospheric input of sulphur and nitrogen (soil, groundwater, surface water).

Biological indicator. Selected organism(s) or populations which are sensitive to chemical changes resulting from atmospheric input of sulphur and nitrogen (forest, fish, invertebrates).

Critical chemical value: The value of a critical chemical component or combination of components (pH, ANC, Al/Ca) above or below which there are no harmful effects to the biological indicator. Acid neutralising capacity (ANC) is the ability of a solution to neutralise the inputs of strong acids to a pre-

SLOVAK REPUBLIC
Critical Loads of Acidity
Receptor: Surface Water



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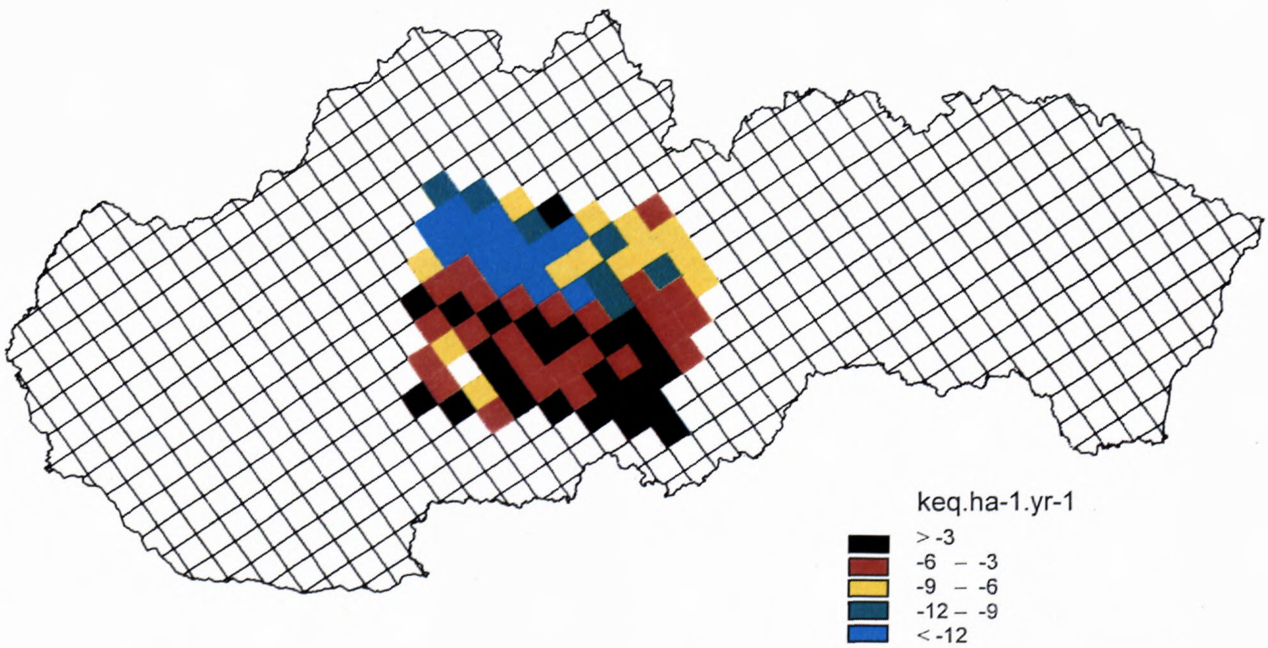
Exceedance of Critical Loads of Acidity
Receptor: Surface Water



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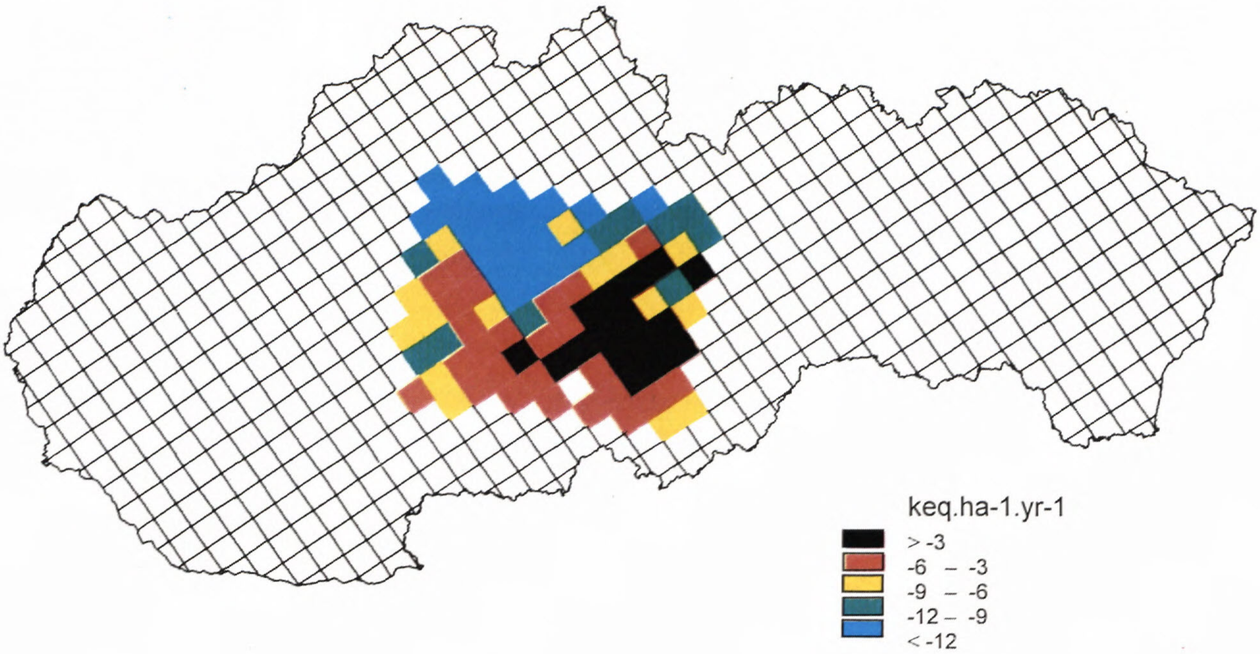
Receptor: Ground Water



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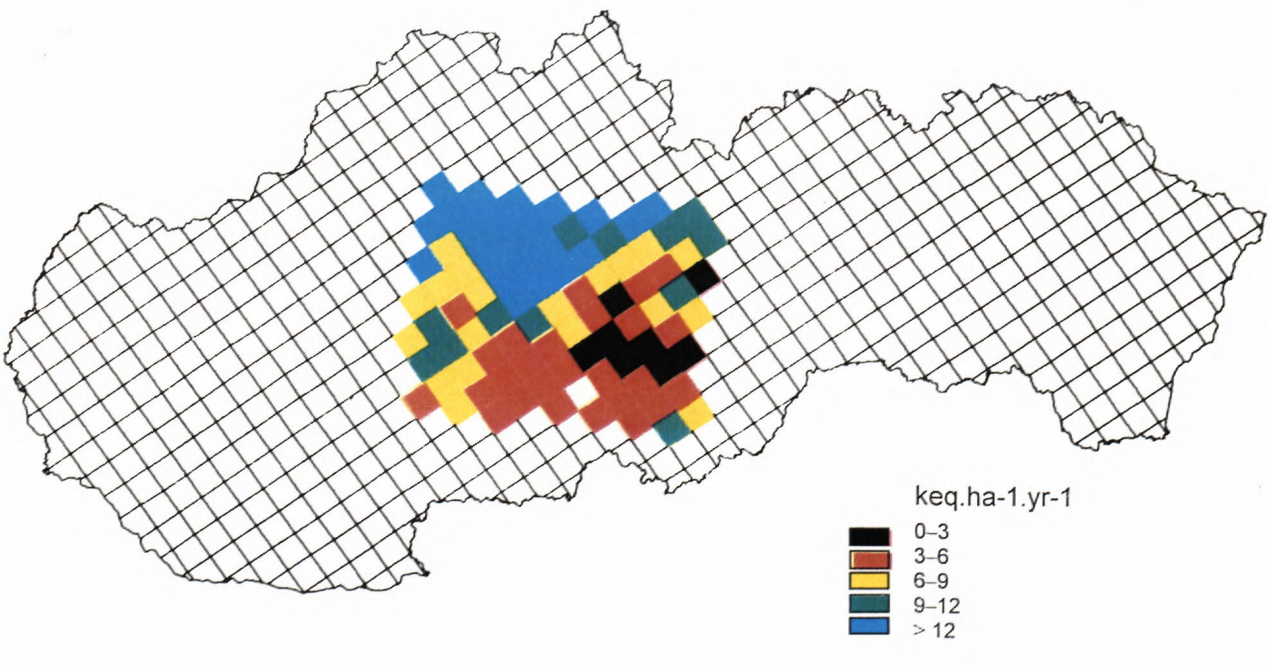
Critical Loads of Acidity
Receptor: Ground Water



selected equivalence. For surface water, ANC has been selected as the critical chemical value and it has been set relative to fish as the biological indicator. ANC is thus the critical concentration for fish. The use of ANC is a simplified approach, in which numerous interacting factors affecting the toxicity to fish, including pH, aluminium and TOC, are grouped into a single variable. Data on water chemistry and general change of fish status have been used in Norway for assessing the ANC for fish. Few fish populations are damaged at ANC concentrations above 20 meq/l. Of the fish species studied, salmon, brown trout and roach were the most sensitive and perch the least sensitive. Although ANC will depend on fish species considered, a value of 20 meq/l seems to be appropriate for the evaluation of critical loads and critical load exceedance for freshwater fish, at least in Norway. Canada has set pH 6.0 (corresponding to an ANC range of 20-40 meq/l for freshwater lakes) as an appropriate chemical threshold used for defining critical loads, disregarding areas with historical pH values below 6.0. This level has been set to protect all aquatic biota. Sweden is using pH > 6.0 and ANC = 50 meq/l as the national threshold value.

The basic steady state surface water chemistry method (SSWC) is based on the fact that sulphates found in surface water originate largely from sea salt spray and polluted deposition and in the method there are ways of correction for sea salt and minor contribution from geological sources, allowing to obtain atmospheric contribution of sulphate in the water (HENRIKSEN et al., 1988, 1990). This sulphate concentration is then used to obtain the weathering rate of the catchment. The chemical data from the pilot area indicate that the geology supplies a significant amount of sulphate to the water. This sulphate is assumed to be balanced largely by base cations BC (Ca+Mg) . Thus, to calculate the critical load, the method must be modified. The atmospheric sulphate contributed to surface and groundwater is estimated by multiplying the sulphur deposition by the ratio of precipitation to run-off. The difference between this value and the sulphate concentration is then geologically supplied sulphate. Since this component is balanced by Ca+Mg, this amount must be deduced from the concentration of base cations to obtain those resulting from weathering and ion-exchange processes. To estimate the ion exchange base cations, a modified F-factor has been used because of the very high weathering rate in the surface and ground water. Ignoring nitrate concentration, the following calculation method results:

$$SO_{4\,dep} = S_{dep} \times P/Q$$

where
S_{dep} = present sulphur deposition in keq/km^2/year
P = annual precipitation in mm
Q = annual run-off in m^3

$$BC_{geol} = SO_{4\,r} - SO_{4\,dep}$$

where
BC_{geol} = base cations of geological origin
SO_{4r} = sulphate concentration in run-off water

$$BC_{wt} = BC_t - BC_{geol}$$

where
BC_{wt} = present weathering rate
BC_t = present Ca+Mg concentration in run-off water

The F-factor is defined as the change in base cation concentration due to a change in the concentration of sulphate

$$F = BC_{wt}/S$$

where
S = base cation concentration at which F=1. The value of 4 meq/l for S has been used in this report

Then: $$BC_w = BC_{wt} - F x SO_{4\,dep}$$

The critical loads of acidity (CL) and critical load exceedance (CL-Ex) are then given:

$$CL = BC_w x Q x 10 \text{ (keq/ha/year)}$$

$$CL\text{-}Ex = S_{dep} - CL \text{ (keq/ha/year)}$$

5. Discussion and conclusions

Results of the calculation of critical loads and exceedances for the acidity of ground- and surface waters for the pilot area of Slovakia is represented on Figs. 1, 2, 3, 4. The colour and value ranges are adjusted to be consistent with international presentations of critical loads.

From the viewpoint of critical loads of acidity the values of surface waters were systematically higher than those for groundwater at correlation of 0.69 (Fig.5).

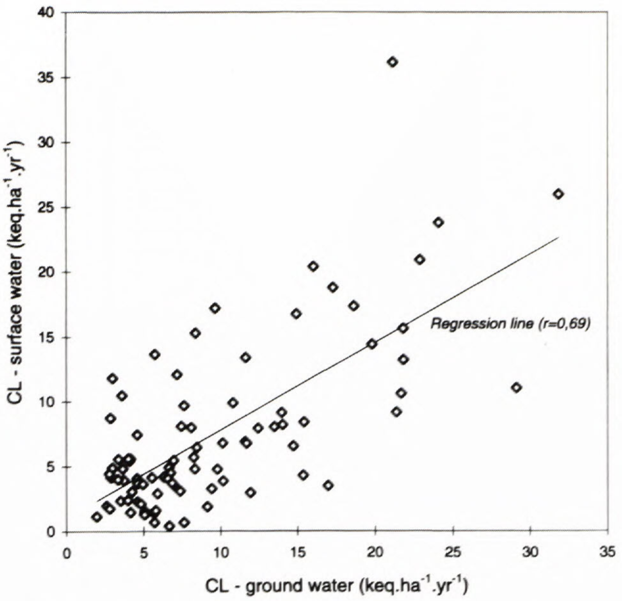


Fig. 5 Relationship between critical loads of ground waters and surface waters

The calculated exceedance values at bcth receptors display high negative values in the greatest part of the pilot area, i.e. they indicate that there are reserves for further contributions of acid deposition. This situation is related to the time of water sampling in the studied territory, i.e. it does not record changes in the chemical composition in time and thus it does not allow to make a prognose. The calculated critical loads reflect in practice the conditions in which chemical composition of water formed, especially geological setting of the territory and hydrodynamic conditions of circulation. The locally higher sensitivity has been caused by outflow from mine works and dispersion of groundwater from the underlier into surface streams. The generally higher sensitivity of the southern part of the pilot area is probably caused by lower velocity of groundwater flow and an important factor is also anthropogenic contamination.

The critical loads and exceedance calculation for natural water presented in the contribution are the first application of this environmental technique in Slovakia. A simple steady-state model (SSWC) has been used, including only sulphur. In the next stage, critical loads of natural water will be calculated in a 10x10 km grid for all Slovakia.

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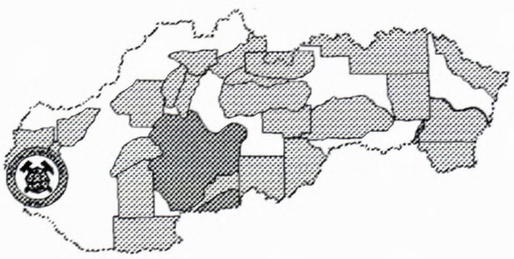

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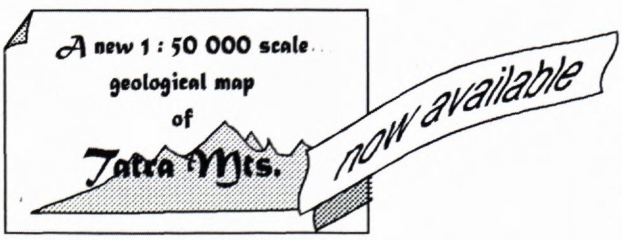

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