Quantitative hardrock hydrogeology in a regional scale

JIŘÍ KRÁSNÝ

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In the hydrogeological characterisation of an area, two quantitative aspects are to be taken into account, namely the geological setting that defines the geometry and anatomy of a hydrogeological environment, and the spatial and time variations of available natural groundwater resources, that mostly depend on recharge possibilities. Methodological approaches aiming to quantify these two aspects in hardrock areas at a regional scale are presented. A hardrock environment can be defined as an intricate hierarchical system consisting of inhomogeneous elements of different extent. A regionally prevailing transmissivity, mostly in units m^2/d with anomalies ranging from 0.1 m^2/d up to 100 m^2/d, seems to be very similar in hardrock environments throughout the world. Considering this regional distribution of transmissivity, natural groundwater resources typically depend on the prevailing climatic conditions. On a background of the Earth's basic climatic zonation (arid, humid, temperate zones), a vertical climatic differentiation (mountains, lowlands, etc.) is of importance. Under favourable conditions in temperate climatic zones natural groundwater resources might reach up to 15 L/s km^2 in the highest parts of hardrock mountainous areas.

Jiří Krásný, Charles University Prague, Faculty of Science, Albertov 6, 128 43 Praha 2, Czech Republic.

Introduction

Most of the present-day hydrogeological projects in the world are of local character. Issues such as contaminant hydrogeology, most water supply problems, groundwater assessment in civil engineering and mining projects are of this type. However, results of regional hydrogeological studies are indispensable for administrators and decision makers, and will have a considerable influence on any land-use planning. They also determine the conditions of an optimum sustainable use of groundwater and its protection in extended areas. Regional results are also of importance for hydrogeologists, in enabling them to draw general hydrogeological conclusions and to compare the conditions in different areas. In this way, factors causing similarities or differences in particular hydrogeological environments can be considered and discussed at regional, national or international levels. Methodologies involving hydrogeological data regionalisation are important especially for hardrock areas as there, in contrast to hydrogeological basins occupied by stratabound sedimentary aquifers, regional approaches in hydrogeological studies have not been common.

When characterising the hydrogeology of an area, two quantitative aspects should be taken into account:

- Static properties of the aquifer system: the geometry and anatomy of hydrogeological bodies and the spatial distribution of their hydraulic characteristics. No hydrogeological environment is homogeneous and isotropic under natural conditions, and the hardrock environment in particular is to be considered as an intricate hierarchical system of hydrogeological inhomogeneities on different scales.
- Geological setting determines the character of a hydrogeological environment within which groundwater, the dynamic element that is the object of our attention, moves and is distributed. Groundwater recharge, which varies in time and space, determines our sustainable natural groundwater resources. Under specific conditions, induced and/or artificial resources might complement the natural resources.

In this contribution, the results of various hydrogeological studies are summarised and a methodology is suggested which aims to help in the assessment of reasonable groundwater development in hardrock areas at a regional scale.

General characteristics of hardrock environments

Geometry and anatomy of hydrogeological bodies

The geometry (horizontal extent and thickness) and anatomy (internal character, distribution and type of porosity) of hydrogeological bodies (aquifers and aquitards) are strongly dependent on the age and character of the last important orogenesis and on the general geological development during the post-orogenic period. The age of the rocks and the tectonic activities control the degree of diagenesis and the relationship between the intergranular and fissure porosity of rocks. Consequently, these features determine the magnitude and distribution of their hydraulic parameters (transmissivity and permeability, storativity). Comparatively old and folded sedimentary rocks have generally lost most of their primary intergranular porosity. Instead of this, fracture porosity prevails. This is especially the case with bedrock, which is usually represented by crystalline (igneous and metamorphic) or by sedimentary, highly cemented and/or folded rocks. The common feature of a hardrock environment, designated as a 'hydrogeological massif', is a vertical sequence of three zones, termed upper weathered, middle fractured and lower massive (Krásný 1996a).

As in the case of the intergranular environment, the permeability of fractures and of fault zones typically decreases through geological time due to different geological processes such as hydrothermal alteration, mineral precipitation and mechanical clogging (Mazurek 2000). Therefore, in any hardrock environment geologically young fractures are the most important for groundwater flow, but as noted by Banks et al. (1993), such fractures might not be recorded by standard field geological and geophysical methods. Relatively soluble rocks such as carbonates, gypsum and salt deposits are the only exceptions to this general rule as their permeabilities generally increase with time.

Hydraulic parameters for identifying hardrock environments

Aquifers and aquitards are distinguished both qualitatively by their geometry and anatomy, and quantitatively by the magnitude of representative hydraulic parameters. The commonly used coefficient of hydraulic conductivity (permeability) was originally derived to characterise an intergranular and homogeneous environment. Subsequently, it was commonly used in a mechanical sense and without taking into account the original preconditions in interpreting the results of aquifer tests in other hydrogeological situations. In hydrogeological environments with a prevailing fracture porosity, however, hydraulic conductivity can be used for hydrogeological interpretations only very cautiously, taking into account scale differences in pathways of groundwater flow and the objectives of the hydrogeological study (Krásný 2001).

In contrast to hydraulic conductivity, the coefficient of transmissivity is defined as a parameter expressing the property of the entire thickness of an aquifer. In a hardrock environment, permeability typically decreases within a depth of some tens of metres from the surface. As water wells sited in such an environment mostly reach depths of between 30 and 60 metres, their transmissivity can be considered as representing the entire hardrock aquifer (Krásný 1993 a). Consequently, transmissivity may well express the capability of the hydrogeological environment for groundwater abstraction. This is generally the main objective of most hydrogeological studies regardless as to whether the groundwater is considered as a natural resource for water supply, a nuisance factor during different underground constructions, or a transport medium for the dispersion of contaminants.

Results of thousands of pumping tests available worldwide in hardrock environments have enabled a quantitative and standardised approach for studying transmissivity distribution under various conditions. In many cases, however, only data of a less reliable character are available in archives. Such data are typically not suitable for determining the exact hydraulic parameters as the coefficient of transmissivity. On the other hand, many of these data are good enough for providing ideas on transmissivity distribution and could be treated statistically. On this basis, an 'index of transmissivity Y' [= log (10^6 q) where q = specific capacity in L/s m] was introduced as one of the comparative regional parameters (Jetel & Krásný 1968). This facilitated a statistical treatment of the available data from pump-tested wells, and the objective classification of transmissivity magnitude and variation is now the principal procedure for drawing important conclusions regarding transmissivity spatial distribution.

Statistical treatment and classification of transmissivity data

Where there exist sufficient transmissivity data for the distribution to be examined by statistical techniques, sample populations based on lithological units, geographical areas, etc., can be characterised by a central value and a statistical parameter expressing the variation in the distribution. If one makes no assumptions about the nature of the distribution, non-parametric parameters such as 'median' and 'interquartile range' are best suited for this purpose. Several authors, however, have noted that distributions of well yield, specific capacity and transmissivity tend to approximate to a log-normal distribution (e.g., Jetel & Krásný 1968, Banks 1998). If one assumes that such distributions are log-normal, they may be characterised by the geometric mean and the standard deviation of log-transformed values. As the index of transmisivity Y is already log-transformed, its distribution can be characterised by the arithmetic mean and standard deviation.

Transmissivity data distribution of particular statistical samples can be graphically represented on probability paper by cumulative relative frequencies of transmissivity values (Fig. 1). Treated values can be expressed by the index of transmissivity Y, by the coefficient of transmissivity T, or by the specific capacity q. The last two parameters should then be expressed in a logarithmic form.

By using this procedure, the range of prevailing transmissivity values $\bar{x} \pm s$ ($\bar{x}$ = arithmetic mean, s = standard deviation of a statistical sample) represent the transmissivity background of a statistically treated hydrogeological environment. Transmissivity values outside the transmissivity background are considered as outlying data – positive or negative anomalies (+A, -A). The far outliers, or extreme anomalies, positive (++A) and negative (- -A), can be found outside the interval $\bar{x} \pm 2s$ (Fig. 1).

To classify transmissivity occurring in different hydrogeological environments, the whole range of possible transmissivity values was separated into six classes representing the orders of transmissivity magnitude introduced by Krásný (1993a) (Table 1). A class (or more than one class) of

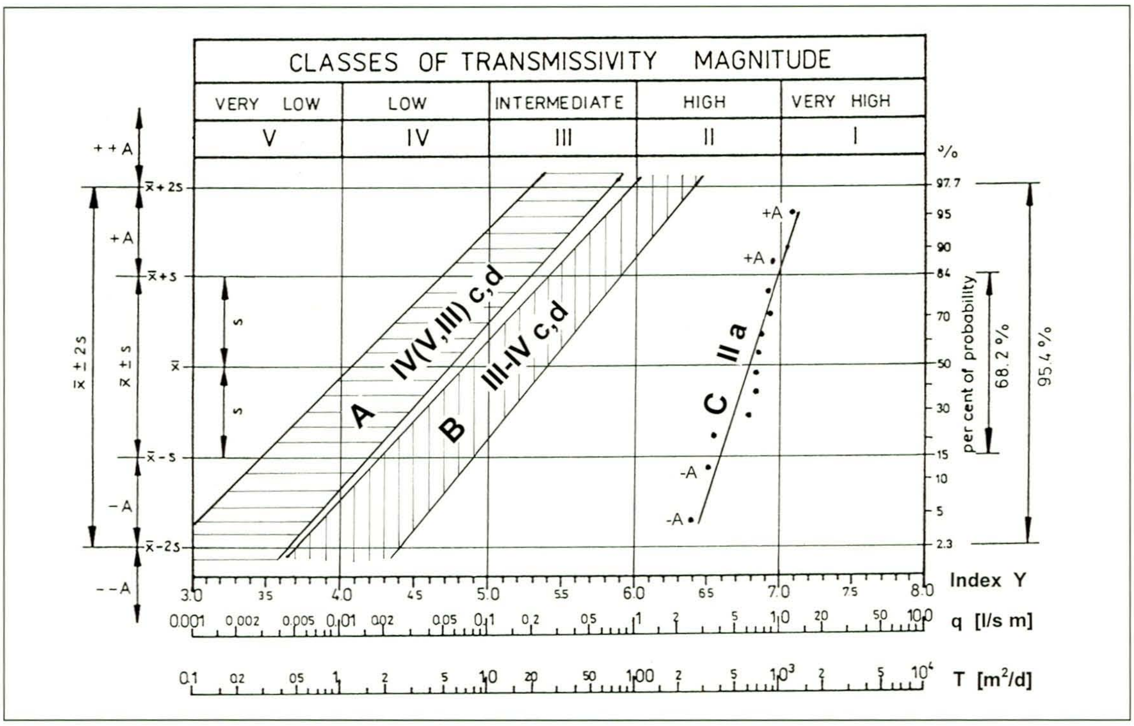

Fig. 1. Prevailing transmissivity and its classification expressed as fields of cumulative relative frequencies (modified after Krásný 1999). q = specific capacity in L/s m, T = coefficient of transmissivity in m²/d, Index Y = index of transmissivity Y (Index Y = log 10^6q, q = specific capacity in L/s m), x̄ = arithmetic mean, s = standard deviation, x̄ ± s = interval of prevailing transmissivity (hydrogeological or transmissivity background) comprising approximately the central 68% of transmissivity values of a statistical sample, ++A, +A, -A, - -A = fields of positive and negative anomalies (+A, -A) and extreme anomalies (++A, - -A), respectively (outside the interval x̄ ± s of prevailing transmissivity).
A - field comprising transmissivity values of the majority of hardrock types, B - field of transmissivity values in crystalline limestones and/or in other hardrocks of higher prevailing transmissivity, C - cumulative relative frequency of transmissivity of fluvial deposits along the Labe River in the Czech Republic (for comparison with transmissivity of hardrocks expressed by fields A and B), indicating not only higher transmissivity but insignificant variability (steep slope of the line) as well (transmissivity class IIa). Classification of transmissivity magnitude and variation after Krásný (1993a).

Table 1. Classification of transmissivity magnitude (after Krásný 1993a).

Coefficient of trans-missivity (m²/d)	Class of transmis-sivity magnitude	Designation of trans-missivity magnitude	Comparative regional parameters approximately corresponding to the coefficient of transmissivity: Non-logarithmic: Specific capacity (L/s m)	Logarithmic: Index Y	Groundwater supply potential	Very approximate expected discharge in L/s of a single well at 5 m drawdown
	I	**Very high**			Withdrawals of great regional importance	> 50
1,000			10	7.0		
	II	**High**			Withdrawals of lesser regional importance	5 – 50
100			1	6.0		
	III	**Intermediate**			Withdrawals for local water supply (small communities, plants, etc.)	0.5 – 5
10			0.1	5.0		
	IV	**Low**			Smaller withdrawals for local water supply (private consumption, etc.)	0.05 – 0.5
1			0.01	4.0		
	V	**Very low**			Withdrawals for local water supply with limited consumption	0.005 – 0.05
0.1			0.001	3.0		
	VI	**Imperceptible**			Sources for local water supply are difficult (if possible) to ensure	< 0.005

transmissivity magnitude is determined after the percentage of the interval $\bar{x} \pm s$ (transmissivity background) belonging to particular classes (Fig. 1) (for a detailed description of the classification system, see Krásný 1993a). The particular classes might indicate the prospect of groundwater supply in different hydrogeological environments (Table 1).

Another important property of a set of transmissivity values (i.e., of a statistical sample) is their variability. This suggests spatial transmissivity changes and, consequently, indicates the internal character (anatomy) of a hydrogeological environment and its degree of hydraulic heterogeneity. Similarly as with transmissivity magnitude, transmissivity variation is also classified by six classes, denominated a to f (Table 2) and based on a standard deviation of transmissivity of a statistical sample. Any transmissivity parameter expressed in a logarithmic form, but preferably the transmissivity index Y, can be used. On probability paper (Fig. 1), samples with low variation will plot along lines with steeper slopes than samples with a large variation.

This classification system enables a realistic assessment of aquifer capability to withdraw groundwater in different areas, and helps in discussions on the influences causing differences in transmissivity values. It also makes it possible to express quantitatively regional hydrogeological conditions in a compact form and to compare them in tables, figures and in hydrogeological maps.

Transmissivity data from aquifer tests have been statistically treated during recent years in many hardrock areas of the Czech Republic, especially within the framework of the countrywide hydrogeological mapping programme. This has brought to light important information on transmissivity distribution. Statistical samples were chosen according to hydrogeological units, rock types and the structural, geomorphological and hydrogeological position of water wells. Particular statistical samples represent areas ranging from several km^2 to tens or hundreds of km^2, with the least used data frequency around seven. Prevailing transmissivity was mostly in units of m^2/d up to slightly more than 10 m^2/d (Krásný 1999, Fig. 1).

Examples from different countries show the possibilities for correlative transmissivity studies in hardrock areas based on this standardised approach. In Poland, Staśko & Tarka (1996) analysed the transmissivity distribution of Precambrian and Lower Palaeozoic gneisses, migmatites, hornfels and amphibolites. In Sweden, Carlsson & Carlstedt (1977) determined cumulative relative frequencies of transmissivity indices Y from gneisses, granites, Algonkian and Cambrian sandstones and Ordovician limestones. A similar procedure was used for transmissivity data analysis from hardrock regions in Ghana (Darko & Krásný 1998, Darko 2001) and in Korea (expressed by Krásný, having used data from Callahan & Choi 1973). Everywhere a similar prevailing transmissivity of hardrocks was determined that can be expressed by the classes IV (V,III) c, d (Fig. 1).

Table 2. Classification of transmissivity variation (after Krásný 1993a).

Standard deviation of transmissivity index Y*)	Class of transmissivity variation	Designation of transmissivity variation	Hydrogeological environment from the point of view of its hydraulic heterogeneity**)
	a	**Insignificant**	Homogeneous
0.2			
	b	**Small**	Slightly heterogeneous
0.4			
	c	**Moderate**	Fairly heterogeneous
0.6			
	d	**Large**	Considerably heterogeneous
0.8			
	e	**Very large**	Very heterogeneous
1.0			
	f	**Extremely large**	Extremely heterogeneous

*) Or logarithmic transformation of any parameter expressing transmissivity
**) Usable also for hydraulic conductivity evaluation

Scale effect in permeability distribution: hierarchy of inhomogeneity elements

The above-mentioned conclusions are based on results of aquifer tests carried out in water wells, mostly to depths of some tens of metres. The character of a spatial distribution of inhomogeneity elements, and consequently also of hydraulic parameters in a fractured environment, strongly depend on the extent of a study area and its relation to the size of respective inhomogeneity elements (Rats 1967, Rats & Chernyshov 1967, Kiraly 1975). Consequently, because of this 'scale effect' values of hydraulic parameters are typically influenced by methods used in their determination.

In a hydrogeological environment characterised by inhomogeneity elements (fracturing) of similar size, transmissivity mean values become closer with increasing testing density within the study area. Finally, these values are practically the same, irrespective of the position of a tested area within this environment (Krásný 2000a). The extent of an area representing the lowest limit above which practically no changes in mean transmissivity values occur is designated as a representative elementary volume (REV). According to Bear (1994), the main characteristic of a REV is that the average value of fluid and solid properties taken over it are independent of its size. Occurrences of larger inhomogeneous elements (e.g., large fracture zones), however, may cause other supplementary differences in transmissivity values and the REV size might expand considerably.

In a fractured hardrock environment, permeability and transmissivity distribution is commonly considered disarranged, without any possibility to be predicted. However, studies on transmissivity distribution in hardrocks of the

Bohemian Massif enabled the definition of a hierarchical system of inhomogeneity elements of different scales designated as local, medium-scale (sub-regional) and regional-scale inhomogeneities (Krásný 2000b).

On a local scale, irregular changes in transmissivity spatial distribution within the 'near-surface aquifer' of hard rocks are common, and are marked by a weathered (upper) zone, often with juxtaposed Quaternary deposits, and by a fractured (middle) zone. These are indicated by differences in yields and transmissivity of nearby wells drilled in the same rock that might reach several orders of magnitude (Fig. 1). In more extensive areas, transmissivity determined by aquifer tests tends to attain considerably closer values both in prevailing ranges and in arithmetic means. As mentioned above, these prevailing values represent the transmissivity background as mentioned above.

Superposed upon this background, however, significant differences in transmissivity magnitude might occur due to the presence of inhomogeneity elements of a higher scale level (medium-scale or sub-regional inhomogeneities). These belong to tectonically strongly affected zones with a considerably higher transmissivity that might be of importance for groundwater abstraction in hardrock environments (Krásný 1996c).

Other authors have commented upon the higher prevailing permeability of rocks in valleys than on slopes and topographic elevations (LeGrand 1954, Krásný 1974, 1998, Henriksen 1995). Following these findings, the hydrogeological environment in fractured rocks should not be considered as regionally homogeneous. It should rather be considered as a complex system where belts of regionally higher prevailing permeability occur, usually following the valleys and depressions. These belts can be perceived as manifestations of inhomogeneity elements of a higher order superimposed on an environment where local inhomogeneity elements can be averaged. The differences in statistically prevailing values between valleys and elevations may reach one order of magnitude or even more. The ratio of arithmetic means ranges from 1.6 to 38 in different types of hydrogeological environments (Krásný 1998). These differences seem to be of general validity, even though they are of distinct magnitudes in different hydrogeological environment. The overall tectonic predisposition of valleys or depressions may well be the main cause of these differences, although, hydrogeological influences would seem to be additional factors leading to increases in these differences, as reported by Krásný (1974).

Regional-scale transmissivity changes were determined in extended hardrock areas in South Bohemia (Krásný et al. 1984). This regional transmissivity distribution evidently reflects the intensity of so-called neotectonic activity, lasting from the Late Tertiary up to recent times. A lower prevailing transmissivity is characteristic of relatively flat areas with negligible neotectonic activity, and higher in zones where neotectonic deformation has been more pronounced (e.g., the Šumava Mts.). The differences in regionally prevailing transmissivity reach more than one order of transmissivity magnitude. This represents an important shift in a regional transmissivity background upon which local changes of transmissivity (positive and negative anomalies) are superimposed (Havlík & Krásný 1998). This might be of practical interest for groundwater supply studies and the siting of waste deposits or deep repositories.

Similar gradual changes in the regionally prevailing transmissivity of hardrocks, caused apparently by different intensities of rock fracturing, have been reported from Norway by Rohr-Torp (1994). His study showed a well yield correlation with the amount of post-glacial isostatic uplift following the Weichselian glaciation. Even though the reasons for the different degrees of fracturing in South Bohemia and in Norway are dissimilar, the comparable effects indicate possibilities of regional variations in transmissivity also in other fracture-dominated environments.

The above-mentioned hierarchical system of transmissivity distribution due to disparate inhomogeneity elements is to be expected in all fractured and double-porosity environments. Practical conclusions should be drawn for conceptual model implementation, groundwater flow modelling, safe yield assessment, well siting and studies on groundwater vulnerability.

Influences of lithology on regional transmissivity distribution in hardrock areas

Results of hundreds of pumping tests carried out in drilled and dug wells in hard rocks within the Czech part of the Bohemian Massif have enabled a quantitative and standardised approach to transmissivity distribution studies. Irregular local permeability changes, determined from results of particular aquifer tests, usually scatter over a wide interval of several orders of magnitude. On the other hand, regionally prevailing transmissivity values (hydrogeological background) resulting from a statistical treatment, mostly belong to classes IV(V,III) c, d, i.e. very low to intermediate transmissivity with moderate to large transmissivity variation – see field A in Fig. 1. Based on the differences in petrographic compositions of rocks and their different ways of fissuring and weathering, differences in hydrogeological properties have also often been considered and expected. An objective comparison of the transmissivity magnitude of particular rocks in the Czech part of the Bohemian Massif, however, indicated only small differences in the regionally prevailing transmissivity of particular areas. Except for some types of rocks, the influence of petrography on transmissivity spatial distribution cannot be considered important. Areas comprising crystalline limestones (marbles) represent the most prominent exception of this rule. Marbles commonly occur as intercalations of variable thickness in bedrock and their hydrogeological properties usually differ considerably from other rock types. The prevailing transmissivity and hydraulic conductivity of marbles is usually a half to one order of magnitude higher compared with other crystalline rocks (Krásný 1999) and might be expressed schematically by field B in Fig. 1 (mostly classes III-IV c,d).

There are some indications that relatively higher transmissivities may be expected in areas underlain by basic igneous rocks and also by some types of granite. On the other hand, phyllites displayed a lower regionally prevailing transmissivity in some areas (Krásný 1993b). No significant transmissivity differences on a regional scale, however, have been demonstrated between most granites and the majority of metamorphic rock types, even though the former have often been considered more permeable. Possible small differences in transmissivity caused by distinctive petrographies of hardrocks are evidently masked by the more important influence of fracturing. Differences in their geomechanical properties, frequency of fracturing and the character of weathering are obvious, however, and may result in local differences in their permeability. At depth, massive granitic rocks seem to be more predisposed to form important fracture zones as many thermal waters are usually associated with them. Thermo-mineral waters in the Czech Republic, such as those at Karlovy Vary (Carlsbad) Spa and Teplice Spa, emanate from granite and quartz porphyry (rhyolite), respectively (Hanzlík & Krásný 1998, Jakeš & Krásný 1998).

The influence of weathering and the presence of generally more highly permeable Quaternary deposits, regoliths, debris and fluvial deposits result in higher transmissivities in wells where hardrocks are covered by these thick, unconsolidated deposits. The transmissivity variation of hardrocks comprising fluvial Quaternary deposits is usually lower than that of hardrocks without a Quaternary cover. This suggests an equalising effect of the hydraulically more homogeneous, Quaternary deposits (Krásný 1993b).

Natural groundwater resources

An assessment of groundwater runoff into rivers draining surrounding aquifers is generally considered the best way to estimate natural (renewable) groundwater resources of the temperate climatic zone on a regional scale. During a mapping programme focused on the assessment of groundwater runoff in the Czech Republic, the total, long-term, mean natural groundwater resources of the whole country were estimated to be as high as 205 m^3/s. The resulting map of the long-term, mean groundwater runoff in the former Czechoslovakia at 1:1,000,000 scale with explanatory notes (Krásný et al. 1981, 1982), might serve as an example of a national cartographic representation of natural groundwater resources. Previous assessments of natural groundwater resources (=recharge) in hardrock areas of Central Europe were low, mostly up to a maximum of 1-2 L/s km^2 (e.g., Hynie 1961). The results of the above-mentioned mapping programme have indicated regionally valid values in the hardrock environment ranging from 1-2 L/s km2 to more than 10 L/s km^2.

To compile such a map, a number of methods for groundwater runoff estimation were tested and compared. For a variety of reasons, mainly due to its objective data processing, the method of Kille (1970) was chosen and employed by all co-authors. The results were compared with a number of other hydrological methods aiming to separate a groundwater component from the total runoff, e.g., Castany et al. (1970), Kliner & Kněžek (1974) and Makarenko (1948). An independent method applying regionally prevailing transmissivity values and morphometric characteristics of the area (Krásný & Kněžek 1977) was also used.

Differences between the results obtained by particular methods were not significant. In some catchments, in the vicinity of mountain summits, the long-term specific groundwater runoff from hardrock areas reaches in excess of 15 L/s km^2. This is mainly because of favourable climatic and geomorphological conditions. The latter result in a relatively high hydraulic gradient of groundwater flow even in this less transmissible hardrock aquifer (Krásný 1999). With decreasing elevation, and mostly due to a decrease in precipitation, the rate of groundwater runoff generally gradually diminishes down to 1-2 L/s km^2. The approximate relationship between climatic and hypsometric conditions and groundwater runoff (= natural groundwater resources) distribution in hardrock areas of the Bohemian Massif is shown in Table 3. Maximum long-term recharge may thus be estimated at more than 300 mm/year. This accounts for more than 20 % of the mean annual precipitation.

Natural groundwater resources in hardrock areas of the Bohemian Massif were also studied in the neighbouring regions of Germany and Poland. Kille´s (1970) method, partly modified by Köpf & Rothascher (1980), was used for regional renewable groundwater resource estimation in Bavaria,

Table 3. Relationship between climatic and hypsometric conditions and groundwater runoff (natural groundwater resources) distribution in hardrock areas of the Bohemian Massif (after Krásný 1996b).

Morphological (hypsometric) unit	Approximate elevation (m a.s.l.)	Mean annual precipitation (mm)	Mean annual evapotranspiration (estimation in mm)	Groundwater runoff (natural groundwater resources – L/s km^2)
Mountains	1,200 – 1,600	1,000 – 1,200	450	10 – 15
Lower mountains	800 – 1,200	800 – 1,000		7 – 10
Piedmont areas	300 – 800	600 – 800		3 – 7
Flat areas, lowlands	less than 300	500 – 600	650	1 – 3

Germany, by Apel et al. (1996). Results of regional studies on groundwater runoff distribution in Poland were presented by Bocheńska et al. (1997) and Kryza & Kryza (1997). The results obtained both in Bavaria and in Poland were quite-comparable with those from the Czech Republic.

Residence time, based on isotope studies, was assessed to between a half to one year for a shallow groundwater flow and up to ten years for a deep one in crystalline rocks of the Bavarian Forest in Germany (Seiler & Müller 1996). Previously, Martinec (1975) had reported a groundwater residence time in crystalline rocks of the Krkonoše Mts. (Czech Republic) of one to two years.

Conclusions

Depending on hydrogeological and climatic conditions, the limiting factor for groundwater resource development may be either:

- hydraulic properties of rocks, or
- groundwater recharge.

A regional assessment and knowledge of these two aspects is indispensable for any decision-making on the sustainable development and protection of groundwater in more extended areas such as regions, states, or even continents.

In arid and semi-arid regions, due to the limited precipitation and high evaporation, natural groundwater recharge typically represents a clear limitation for groundwater abstraction. Intensive groundwater withdrawals may result in a long-term overdraft.

On the other hand, within the Earth's temperate climatic zone, a relationship between groundwater abstraction possibilities of different hydrogeological environments, given by their hydraulic parameters, and the available natural groundwater resources determines what is effectively a safe yield for an area. In hardrock environments where high natural (renewable) groundwater resources reach up to 10-15 L/s km^2 in some catchments in the vicinity of mountain summits, recharge is sufficient to cover abstraction possibilities that are limited only by the transmissivity of the rocks. Mountains with their surprisingly high natural groundwater resources, in spite of their relatively low transmissivity, commonly represent source areas high enough to maintain flow in water courses in adjacent piedmont zones during dry periods. Therefore, when considering the formation of natural groundwater resources (groundwater recharge) against a background of the Earth's climatic zonation (arid, humid, temperate, etc.) the vertical climatic zonation mostly arising from hypsometric differences (mountains, lowlands, etc.), should also be taken into account.

Under these conditions, and considering the present-day general trends towards water management optimisation and also increases in existing water demand, adequately sited water wells or other water intake systems in hardrock areas can cover the requirements on water supply for small communities, plants or farms, and also for domestic water consumption. In areas with high transmissivity of hardrocks, the groundwater abstraction possibilities might even be high enough to supply small towns. Therefore, within hardrock areas with sufficient water resources, scattered water intake sites can effectively cover the water supply demands of a large number of consumers. A hydrogeological basis, i.e., an adequate understanding of transmissivity and permeability distribution, is an essential factor in attaining this goal.

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