Topographic setting, proximity to the rivers and technical factor influence on the well yield of the dolomite aquifers in Slovenia

Vpliv topografske lokacije, bližine rek in tehničnih faktorjev na izdatnost vodnjakov v slovenskih dolomitnih vodonosnikih

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Abstract: Influences of topographical setting and technical factors which contribute to different hydraulic values of transmissivity, hydraulic conductivity, specific capacity and maximum yields in dolomite aquifers in Slovenia, are discussed. Topographical setting of wells and their proximity to rivers show great influence, while technical factors like well depth and penetration degree are of no importance. The presented factors should be considered in advance when planning new locations for water exploitation wells, to predict hydraulic parameters and locate well adequately.

Povzetek: V prispevku so predstavljeni vplivi lokacije in tehnične izvedbe vodnjakov na vrednosti transmisivnosti, koeficienta prepustnosti, specifične izdatnosti in maksimalnih pretokov v dolomitnih vodonosnikih v Sloveniji. Topografska lokacija in bližina vodnjakov do rek imata velik vpliv na vrednosti hidravličnih parametrov, medtem ko globina vodnjakov in stopnja popolnosti nimata opaznega vpliva.

Key words: topographical setting, well depth, dolomite aquifers, Slovenia
Ključne besede: topografska lokacija, globina vodnjakov, dolomitni vodonosniki, Slovenija

Introduction

Wells in Slovenia are drilled into various lithological units, mostly in alluvial sediments and sedimentary rocks. Among the latter, dolomites are preferable compared to the limestones or sandstones. Dolomite rocks cover about 8 % of Slovenia's surface and occur from Permian through most of the Triassic, and Jurassic, Cretaceous and up to Paleocene (Verbovšek, 2003). As the water well supply is increasingly focused into groundwater exploitation, knowledge of several factors which influence the well yield, is essential. The purpose of this paper is to analyze the influence of several factors on four hydraulic parameters, namely hydraulic conductivity *K*, transmissivity *T*, specific capacity *q* (=Q/s), which represents well yield divided by belonging drawdown, and maximum yield Q_{max}, representing the highest value of well discharge obtained by pumping on the well.

Scientific paper

Several studies of influencing factors have been made to explain variations in well yields by examining factors in various locations and rock types (HENRIKSEN, 1995; SUN, 1995; MABEE, 1999; WLADIS AND GUSTAFSON, 1999; EFTIMI, 2003; HENRIKSEN, 2003). Slovenia has an intense topographical relief, ranging from sea surface up to 2864 m. The relief greatly influences the distribution of rainfall and along with the geological properties characterizes the runoff and aquifer recharge. Topographical setting should therefore be of greater importance to the aquifer yield. Also, proximity to rivers is studied in this paper, as aquifers near the rivers can be recharged directly from the surface water bodies. Greater well depth can contribute to higher yield, as the greater number of fractures can be captured and fully penetrating wells should similarly have higher yield due to the capturing of whole aquifer thickness. The influence of four factors (topographical location, proximity to rivers, well depth and degree of partial penetration) is presented and discussed in this paper and comparison of the results is given with the other studies.

MATERIALS AND METHODS

Hydraulic parameters have been obtained from hydrogeological reports of several geological and drilling companies in Slovenia. Aquifer tests described in the reports were performed by submersible pumps or by airlift tests. Even if the parameters obtained by the latter tests do not characterize the aquifer properties exactly, they can still be used for aquifer characterization, as errors usually do not exceed one order of magnitude (WLADIS AND GUSTAFSON, 1999). It should be noted that in all hydrogeological reports, the methods of Cooper-Jacob and Theis were used for determination of K and T, and these are not always applicable to fractured aquifers. The values of hydraulic conductivity, which is further recalculated from the transmissivity via the equation $T=Kd$, are additionally influenced by the estimated values of aquifer thickness d, and sometimes this parameters not well known. All these factors can cause the unreliability of calculated hydraulic parameters, especially K.

For the study of influence of different factors on well yield, a hydrogeological relational database was constructed. Database consists of several linked tables, describing *main data* (ID, location, name, depth ...), *lithology* (depth of different beds, their age ...), *hydrogeology* (discharge, transmissivity, hydraulic conductivity, specific capacity ...), *casing* and *other data*. The location of wells was obtained from a map of dolomite outcrops in Slovenia, developed in a GIS environment, and based on the Base Geological Map of Yugoslavia (OGK, covering whole Slovenia) in scale 1:100.000.

For investigation of topographic control the wells were separated into 6 topographic settings (Figure 1): V (valley bottoms), R (ridges), P (plateaus), S (slopes), F (flatlands in topographic lows) in H (foothills), and topography was defined from the topographical map in scale of 1:25.000 (national map TK25). For the study of proximity to rivers wells were divided into two classes, being closer (<200 m) or farther (>200 m) from the major watercourses, marked as rivers on the 1:25.000 topographic maps TK25 of Slovenia. The limit of 200 m was chosen for two reasons. The main one is that the value of 200 m is usually taken as a radius of influence of the well in short-term transient pumping conditions, so the wells within this distance from the rivers can be influenced by infiltration from the rivers. In addition, the 200 m was chosen as a upper limit of the classes of MABEE (1999) because even with this dataset, the number of data for wells near the rivers is small compared to those farther away. With further division into smaller classes, the number of data of nearer wells and the quality of analysis would decrease. Of course, this limit is purely artificial, so the results could differ for some other classification. Among the technical factors, well depth and degree of partial penetration were analyzed. For the former, data were classified into five classes according to well depth, each class occupying 50 m (0-50 m, 50-100 m, 100-150 m, 150-200 and > 200 m). In similar way, wells were divided into two categories – fully or partially penetrated wells.

Statistical methods were used for the analysis, as they are known to represent the best method for description and prediction of water well parameters (EFTIMI, 2003). The distribution and the values of geometric mean and geometric standard deviation are given along with the other data. For all four influences, the differences among the classes were compared by two statistical tests (t and M-W), described later in the text.

RESULTS AND DISCUSSION

Distribution of data

Visual inspection of probability plots was checked for 8 different distributions. The results show that lognormal distribution fits best to all studied parameters. Verification of lognormal distribution for most parameters was further confirmed by statistical normality tests, namely Kolmogorov-Smirnov (K-S), its Lillliefors' modification (L) and Shapiro-Wilk's (W) test (Table 1). The latter is thought to be the most powerful among all, especially in case of small data samples and for the lognormal distribution (DE SÁ, 2003). According to K-S test, all parameters are distributed lognormally, and L and W tests shows some of the parameters distributed as non-lognormal on 95 % confidence level. As lognormal distribution was confirmed for almost all parameters by statistical tests, two different tests were used for analyzing the differences among the groups. The first, student's *t-test* assumes normal distribution of data, whereas for the nonparametric *Mann-*

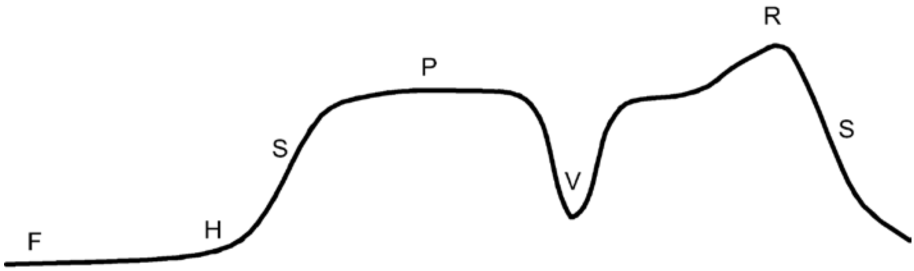

Figure 1. Topography classes. V: valley bottoms, R: ridges, P: plateaus, S: slopes, F: flatlands in topographic lows and H: foothills.

Slika 1. Topografski razredi. V: doline, R: grebeni, P: planote (višje ležeče izravnave), S: pobočja, F: ravnine (nižje ležeče), H: vznožja

Table 1. P-values of normality testing of log-transformed data (N: number of samples, K-S: Kolmogorov-Smirnov test, L: Lilliefors test, W: Shapiro-Wilks test). Asterisk * indicates significant results on 95 % level and therefore non-lognormal distribution of data. Lower values indicate higher deviations from normality.
Tabela 1. Rezultati testiranja normalne porazdelitve (N: število vzorcev, K-S: Kolmogorov-Smirnov test, L: Lilliefors test, W: Shapiro-Wilks test). Zvezdica * označuje signifikantne rezultate na 95 % stopnji zaupanja in torej porazdelitev, ki ni normalna. Manjše p-vrednosti kažejo na večja odstopanja od normalnosti.

Parameter	N	K-S	L	W
K	122	< 0.1	< 0.01 *	< 0.01 *
T	105	> 0.2	< 0.05	0.03 *
q	299	> 0.2	> 0.2	0.22
Q_{MAX}	286	< 0.1	< 0.01 *	0.01 *

Whitney test distribution is not important. As the data were found to be lognormal, the values are presented by geometric mean x* and geometric standard deviation s* (LIMPERT ET AL., 2001), as these should be used in case of this distribution and especially when describing the heterogeneous media (ABOUFIRASSI AND MARIÑO, 1984; DE MARSILY ET AL., 2005).

Topographical setting

Geometric means of parameters (Table 2) indicate that the values of most parameters can be found in flatlands (*F)*, with this topographical setting being there times on first and once on second place. The values of parameters *K* and *T* are about one or more orders of magnitude greater in this class than in the others. Flatlands are followed by valleys (*V)* (once on first and three times on second place). The lowest values are observed in plateaus or high flats *(P)* (three times on last place), whereas the other three topographic settings (ridge *R*, foothill *H* and slope *S*) lie in between. Differences among the topographic groups were further tested by t-tests and M-W tests. Results (Table 2, Figure 2 for T and Q_{max}) show significant differences between classes V↔S, P↔F, S↔F, and also V↔R, V↔H, V↔P for practically all parameters, and non-significant differences between V↔F, R↔P, R↔S, R↔H, P↔H and S↔H. According to the values of hydraulic parameters, the topographic classes of valleys and also flatlands can be therefore generally distinguished from the ridges, slopes, foothills and plateaus. Less productive settings are indistinguishable among themselves, and the same conclusion can be made for the most productive groups (V and F) among themselves. Lower values of parameters on the slopes can be explained by greater runoff and lesser infiltration compared to flat areas. The water also tends to drain the higher topographic locations towards the lower locations, so the latter receive additional recharge this way, plus possible recharge from surface waters. Comparison to other studies (MABEE, 1999, LEGRAND, 1967) shows similar results, as the greatest values of well yield could be found in the topographic lows (valley/fjord bottoms and flats) and there existed no difference among the wells in valley bottoms and among the ones in flats (HENRIKSEN, 1995). Insignificant differences between some of the classes can be attributed to great variability, so the range of well yield values overlaps between topographic categories (YIN AND BROOK, 1992).

Table 2. Values and results of M-W and t-tests for influence of topography on hydraulic parameters (95 % confidence level). x*: geometric mean, s*: geometric standard deviation, N: both tests are non-significant, Y: both tests are significant. When these two tests differ, the first letter indicates results of M-W tests and second of t-tests. Some M-W-tests were not possible due to insufficient data and are indicated by -.

Tabela 2. Vrednosti in rezultati M-W in t-testov za vplive topografske lokacije na hidravlične parametre (95 % stopnja zaupanja). x*: geometrijska srednja vrednost, s*: geometrijski standardni odklon. N: oba testa nesignifikantna, Y: oba testa signifikantna, v ostalih primerih, kjer se rezultati testov razlikujejo, označuje prva črka rezultate M-W testa in druga t-testa. Ponekod M-W testi zaradi premajhnega št. podatkov niso bili možni in so označeni z -.

Hydraulic conductivity / Koeficient prepustnosti K (m/s)									
N	**x***	**s***		**V**	**R**	**P**	**S**	**F**	**H**
69	-5.35	1.16	**V**alley	-	-	-	-	-	-
2	-5.94	0.37	**R**idge	N	-	-	-	-	-
24	-5.89	0.95	**P**lateau	Y	N	-	-	-	-
17	-6.14	1.09	**S**lope	Y	N	N	-	-	-
5	-4.63	0.12	**F**latland	N	NY	Y	Y	-	-
1	-6.30	-	Foot**H**ill	-N	-N	-N	-N	-Y	-
Transmissivity / Transmisivnost T (m^2/s)									
N	**x***	**s***		**V**	**R**	**P**	**S**	**F**	**H**
66	-3.24	1.13	**V**alley	-	-	-	-	-	-
5	-3.88	1.51	**R**idge	N	-	-	-	-	-
20	-4.34	0.77	**P**lateau	Y	N	-	-	-	-
8	-4.33	0.59	**S**lope	Y	N	N	-	-	-
4	-2.72	0.11	**F**latland	N	N	Y	Y	-	-
1	-3.94	-	Foot**H**ill	-N	-N	-N	-N	-Y	-
Specific capacity / Specifična izdatnost q (l/s/m)									
N	**x***	**s***		**V**	**R**	**P**	**S**	**F**	**H**
164	-0.21	0.80	**V**alley	-	-	-	-	-	-
9	-0.76	0.45	**R**idge	Y	-	-	-	-	-
36	-1.02	0.96	**P**lateau	Y	N	-	-	-	-
54	-0.61	0.90	**S**lope	Y	N	Y	-	-	-
14	-0.09	0.85	**F**latland	N	NY	Y	N	-	-
36	-0.69	1.16	Foot**H**ill	Y	N	N	N	N	-
Maximum discharges / Maksimalni pretoki Q_{max} (l/s)									
N	**x***	**s***		**V**	**R**	**P**	**S**	**F**	**H**
117	0.78	0.56	**V**alley	-	-	-	-	-	-
9	0.21	0.32	**R**idge	Y	-	-	-	-	-
44	-0.06	0.66	**P**lateau	Y	N	-	-	-	-
46	0.31	0.60	**S**lope	Y	N	Y	-	-	-
16	0.50	0.58	**F**latland	N	N	Y	N	-	-
40	0.35	0.81	Foot**H**ill	Y	N	Y	N	N	-

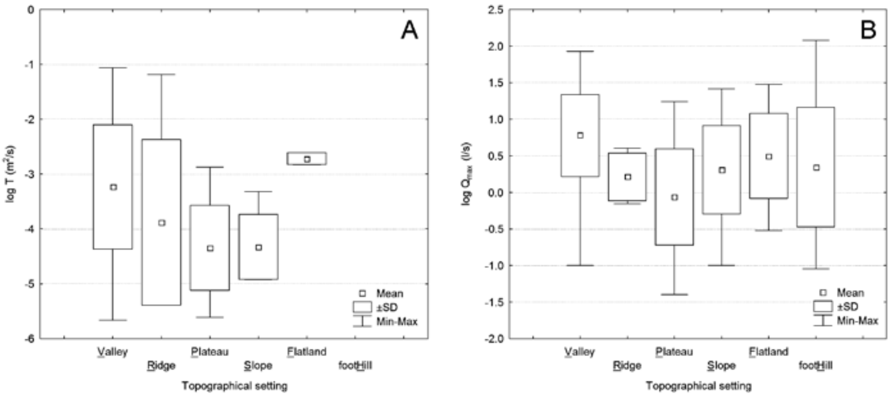

Figure 2. Box-plots of transmissivity (A) and maximum discharges (B) classified by topographical setting on Figure 1. Due to only one value in the Foothill class, this class is not shown in (A).

Slika 2. Škatlasti diagrami transmisivnosti (A) in maksimalnih pretokov (B), razdeljenih po topografski lokaciji (sl. 1). Podatki za razred Vznožje (H) niso prikazani za primer (A), ker je št. vzorcev premajhno (N=1).

Proximity to rivers

Results in Table 3 indicate that values are always higher in wells close to the rivers, being greatest (almost two orders of magnitude) for transmissivity. Differences are significant by both tests for all parameters except for hydraulic conductivity *K*. However due to very low number of data near the rivers (N=2), the results for *K* are to some extent unreliable. When compared to study of MABEE (1999), wells were in his case classified into 4 classes (<60, 60–100, 100–200 and>200 m) of proximity to surface water bodies, no significant differences were observed among the categories. Proximity to the rivers obviously has a major effect on hydraulic parameters, and this can be explained by recharge from the nearby rivers. In some of the wells the water level prior to and after the pumping was only a few meters below the surface, so the hydraulic connection between the well and the rivers could be established. However, this can not be checked for all wells, as the database was not complete and for many of the analyzed parameters the water table levels were not known. It is expected, nevertheless, that the proximity to the rivers should have an influence only on parameters Q_{max} and *q*, and not also on *K* and *T*, which are defined as aquifer properties. The results for *K* as discussed above, somewhat unreliable, and the explanation why the values of T are also significantly different, can be given in two ways. The rocks can be more intensively fractured in the vicinity of rivers as many valleys follow the tectonic lineaments. The influence of these lineaments can not be confirmed, as there is not enough data on tectonic properties of the rocks. Secondly, the *K* and *T* can be incorrectly calculated as the Cooper-Jacob and Theis equations do not always apply to fractured aquifers (VERBOVŠEK, 2005), so the values of these two parameters are somewhat unreliable.

Table 3. Influence of proximity to major rivers on hydraulic parameters. FAR indicates wells located more than 200 m from the rivers and NEAR those within this range
Tabela 3. Vplivi bližine rek na hidravlične parametre. FAR označuje vodnjake, oddaljene več kot 200 m od večjih rek, NEAR pa bližnje

	N	x*	s*	Min	Max	t &MW
Hydraulic conductivity / Koeficient prepustnosti K (m/s)						
Near	2	-4.55	0.66	-5.02	-4.09	N
Far	116	-5.58	1.13	-8.06	-3.41	
Transmissivity / Transmisivnost T (m^2/s)						
Near	7	-1.77	0.69	-3.11	-1.06	Y
Far	95	-3.68	1.06	-5.66	-1.19	
Specific capacity / Specifična izdatnost q (l/s/m)						
Near	45	0.30	0.76	-1.56	1.55	Y
Far	253	-0.55	0.89	-2.60	2.05	
Maximum discharges / Maksimalni pretoki Q_{max} (l/s)						
Near	34	1.11	0.47	-0.28	1.78	Y
Far	238	0.37	0.67	-1.40	2.08	

Well depth

Results (Table 4, Figure 3 for T and Q_{max}) show no systematic relation of decreasing hydraulic parameters with well depth. Significant differences though exist between some groups, but they are more or less random and have no logical explanation. This is in agreement with study of Loiselle and Evans (1995), where no change in fracture yield was observed with increasing depth. The explanation for non-significant differences could be that although there is a tendency to increase water supply by increasing the depth of a well, this chance also decreases because the interconnecting fractures and the ability of rocks to store and transmit water decrease with depth (LeGrand, 1967). However, this effect can be observed in deeper wells (more than few thousand meters), usually drilled for the oil exploitation. In this study, the majority of the analyzed wells are drilled to the depth of 300 m, and the fractures occur through the whole depth interval. The well depth should therefore not exhibit any influence of the well productivity, as observed. Other authors (Mabee, 1999) have nevertheless found that some of the shallower wells are more productive than the deeper ones, but the wells were located in metamorphic rocks, which are not directly comparable with the dolomites. To conclude, heterogeneity is most likely one of the major factors influencing well yield with depth, if this does not exceed some hundreds of meters.

Partial penetration

Values of geometric mean are higher for partially penetrating wells, except for *K*, where these two values are approximately the same. However, both t and M-W tests do not prove the differences, as seen from Table 5. This factor thus does not influence the parameters significantly. Similar results that transmissivity obtained by Cooper-Jacob method is affected only minimally by partial penetration, was observed in confined aqui-

Table 4. Influence of well depth. Classes are divided into five groups: 1: 0-50 m, 2: 50-100 m, 3: 100-150 m, 4: 150-200 m, 5: more than 200 m of well depth
Tabela 4. Vplivi globine vodnjakov. Vodnjaki so razdeljeni v pet razredov: 1: 0-50 m, 2: 50-100 m, 3: 100-150 m, 4: 150-200 m, 5: več kot 200 m globine

Hydraulic conductivity / Koeficient prepustnosti K (m/s)								
N	**x***	**s***		**1**	**2**	**3**	**4**	**5**
1	-4,49	-	**1**	-	-	-	-	-
9	-5,44	1,26	**2**	N-	-	-	-	-
17	-4,87	0,64	**3**	N-	N	-	-	-
15	-5,38	0,88	**4**	N-	N	NY	-	-
16	-6,04	1,09	**5**	N-	N	NY	N	-
Transmissivity / Transmisivnost T (m^2/s)								
N	**x***	**s***		**1**	**2**	**3**	**4**	**5**
0	-	-	**1**	-	-	-	-	-
5	-3,81	0,69	**2**	-	-	-	-	-
16	-2,72	0,75	**3**	-	Y	-	-	-
12	-3,30	0,92	**4**	-	N	N	-	-
16	-3,93	1,06	**5**	-	N	Y	N	-
Specific capacity / Specifična izdatnost q (l/s/m)								
N	**x***	**s***		**1**	**2**	**3**	**4**	**5**
17	-0,60	0,99	**1**	-	-	-	-	-
44	-0,64	0,99	**2**	N	-	-	-	-
57	-0,16	0,77	**3**	NY	Y	-	-	-
49	-0,55	0,81	**4**	N	N	Y	-	-
33	-0,86	1,02	**5**	N	N	Y	N	-
Maximum discharges / Maksimalni pretoki Q_{max} (l/s)								
N	**x***	**s***		**1**	**2**	**3**	**4**	**5**
34	0,13	0,76	**1**	-	-	-	-	-
66	0,23	0,71	**2**	N	-	-	-	-
79	0,72	0,58	**3**	Y	Y	-	-	-
62	0,66	0,46	**4**	Y	Y	N	-	-
45	0,35	0,76	**5**	N	N	Y	Y	-

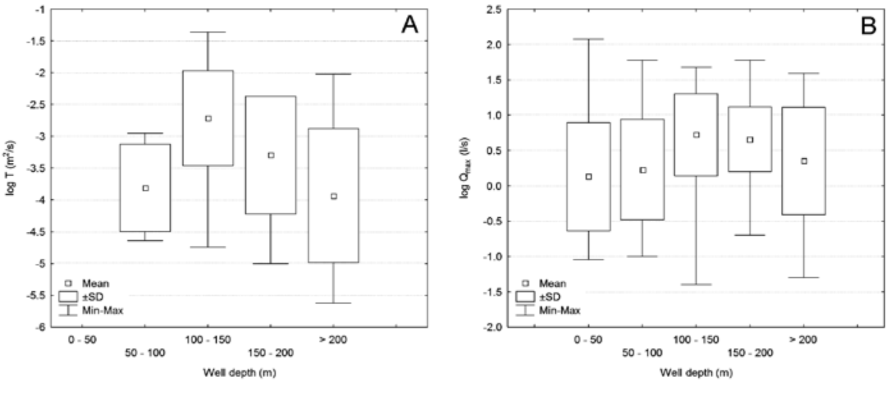

Figure 3. Box-plots of transmissivity (A) and maximum discharges (B), classified by well depth
Slika 3. Škatlasti diagrami transmisivnosti (A) in maksimalnih pretokov (B), razdeljenih po globini vodnjakov

Table 5. Influence of partial penetration of wells (fully or partially penetrating well)
Tabela 5. Vplivi popolnosti vodnjakov. *Fully*: popoln vodnjak, *Partially*: Nepopoln vodnjak.

	N	x*	s*	Min	Max	t & M-W
Hydraulic conductivity / Koeficient prepustnosti K (m/s)						
Fully	8	-5,55	0,89	-6,66	-4,26	N
Partially	114	-5,57	1,13	-8,06	-3,41	
Transmissivity / Transmisivnost T (m^2/s)						
Fully	5	-4,09	0,66	-4,86	-3,28	N
Partially	101	-3,53	1,14	-5,66	-1,06	
Specific capacity / Specifična izdatnost q (l/s/m)						
Fully	39	-0,60	0,74	-2,60	1,55	N
Partially	259	-0,47	0,96	-2,60	2,05	
Maximum discharges / Maksimalni pretoki Q_{max} (l/s)						
Fully	32	0,29	0,65	1,48	1,48	N
Partially	243	0,46	0,68	2,08	2,08	

fers (Halford et al., 2006). Higher values of most parameters in partially penetrating wells are contradictory to expectations that well yields should be higher in fully penetrating wells, as longer well screens can be placed than in partially penetrating ones (Kruseman and de Ridder, 1994). The non-significant results can be interpreted by the fact that the wells, drilled in productive aquifer with high transmissivity are usually not drilled to capture the whole aquifer depth, if they encounter the productive fractures. The partially penetrating wells therefore mostly capture the aquifers with good yield. In addition, the wells which penetrate more than 70 % of the complete aquifer thickness, are regarded as fully-penetrating, as they activate the whole thickness. All of these factors generate the insignificant differences between the two classes.

Conclusions

The results can be concluded in following points:

All data is lognormally distributed by visual estimates of probability plots. Statistical testing by Kolmogorov-Smirnov, Lilliefors and Shapiro-Wilks' tests confirms lognormal distribution for most of data. The selection of non-parametric Mann-Whitney or parametric t-tests for distinguishing the classes does not greatly influence the results, as they give the same significant results in most cases (but not the same p-values).

Topographic setting has great effect on hydraulic parameters. The highest values of hydraulic parameters can be found in flatlands, followed by locations in valleys. The least productive settings are the plateaus or high flats, whereas the other three (ridges, foothills and slopes) lie in between. Significant differences are confirmed by t and M-W tests for those classes which have the greatest or the lowest values. Influence of *proximity to rivers* shows the wells closer to rivers to have higher hydraulic values than those farther away. This is confirmed by all tests except for *K*. All parameters are higher in the first groups, what can be explained by recharge of the wells from the rivers; however this conclusion can be made only for Q_{max} and *q*, and not also on *K* and *T*. The latter parameters can be incorrectly calculated, as discussed below, and the rocks can be also more intensely fractured in the vicinity of the rivers, as valleys frequently follow tectonic lineaments. *Well depth* does not influence the hydraulic parameters significantly. Although there are noticeable differences between the 50 m thick classes, they are more or less random. The degree of *partial penetration* does not influence any of the parameters.

To describe the data more accurately, hydraulic conductivity and transmissivity should be calculated by appropriate methods for fractured aquifers (VERBOVŠEK, 2005), as from reports used in this study it is not clear whether the values of *K* and *T* could stand for the values of the fractures or of the matrix. In all hydrogeological reports, the methods of Cooper-Jacob and Theis were used for determination of *K* and *T*, and these are not always applicable to fractured aquifers. Appropriate usage of these methods would eliminate these uncertainties and enable to compare the influences of matrix versus fractures. Some more factors, not available to this study, could be studied, such as detailed petrographic studies of dolomites or proximity to tectonic lineaments. When planning new locations for water exploitation wells, all the presented factors should be considered in advance, to predict hydraulic parameters and locate well adequately.

POVZETEK

Vpliv topografske lokacije, bližine rek in tehničnih faktorjev na izdatnost vodnjakov v slovenskih dolomitnih vodonosnikih

V prispevku so predstavljeni vplivi topografske lokacije, bližine rek, globine ter stopnje popolnosti vrtin in vodnjakov (v nadaljevanju "vodnjakov") na naslednje hidravlične parametre: transmisivnost *T*, koeficient prepustnosti *K*, maksimalne pretoke Q_{max} ter na specifično izdatnost *q* (=Q/s). Podatki so pridobljeni iz hidrogeoloških poročil o vrtinah in vodnjakih v dolomitnih vodonosnikih v Sloveniji, nekateri manjkajoči podatki pa so bili dobljeni s pomočjo karte dolomitnih plasti v GIS okolju, izdelane na osnovi OGK.

Pri določanju vpliva topografske lokacije so bili vodnjaki razdeljeni v 6 topografskih razredov (sl. 1) po karti v merilu 1:25.000: V (doline), R (grebeni), P (planote oz. višje ležeče izravnave), S (pobočja), F (nižje ležeče ravnine) in H (vznožja). Za analizo vplivov bližine rek so bili ločeni v dva razreda glede na oddaljenost (manj in več kot 200 m) do vodotokov, označenih kot reke na kartah 1:25.000. Globina vodnjakov je bila razdeljena v pet razredov po 50 m, stopnja popolnosti vodnjakov pa v dva razreda glede na to, ali je vodnjak izvrtan do neprepustne podlage ali ne. Rezultati so predstavljeni s statističnimi vrednostmi (EFTIMI, 2003; DE SÁ, 2003), razlike med razredi pa so določene z neparametričnimi Mann-Whitney (M-W) in parametričnimi t-testi.

Rezultati v nadaljevanju so podani ločeno za vsak parameter. *Porazdelitve.* Vsi para-

metri so porazdeljeni logaritemsko normalno (tabela 1), kar dokazujejo vizualne ocene porazdelitev ter večina od treh testov normalnosti (Kolmogorov-Smirnov, Lilliefors ter Shapiro-Wilks). *Vpliv topografije*. Geometrične srednje vrednosti večine hidravličnih parametrov so najvišje v nižje ležečih ravninah (F), saj so vrednosti *T* in *K* tudi do dveh redov velikosti višje kot pri ostalih razredih (tabela 2, slika 2). Ravninam sledi razred dolin (V), najnižje vrednosti pa se nahajajo v planotah (P). Vrednosti v ostalih razredih (grebeni R, vznožja H in pobočja S) ležijo med omenjenimi. Medsebojna testiranja med razredi kažejo signifikantne razlike med razredi V↔R, V↔S, V↔H, P↔F, S↔F in V↔P za skoraj vse parametre ter nesignifikantne med razredi V↔F, R↔P, R↔S, R↔H, P↔H in S↔H. Vrednosti parametrov visoko izdatnih razredov se torej dokazljivo ločijo od nizko izdatnih, nasprotno pa se visoko izdatni (npr. doline in ravnine) ne ločijo med seboj. Rezultati so v skladu z opazovanji številnih avtorjev (LeGrand, 1967; Henriksen, 1995; Mabee, 1999), kjer so, podobno, najbolj izdatni vodnjaki locirani v topografsko nižje ležečih predelih. *Bližina rek* ima precejšen vpliv, saj so vrednosti vseh parametrov višje v razredu oddaljenosti manj od 200 m. Razlike povsod, razen pri koeficientu prepustnosti *K*, potrjujejo tudi M-W in t-testi (tabela 3). Vendar so tudi rezultati testov za *K* vprašljivi, saj je število podatkov za en razred izredno majhno (N=2). Rezultati se sicer ne skladajo s analizo Mabee-ja (1999), verjetno zato ker je bila v slednjem primeru uporabljena drugačna klasifikacija v štiri razrede (<60, 60–100, 100–200 ter >200 m) z manjšo oddaljenostjo od rek. Večjo izdatnost vodnjakov lahko razložimo z napajanjem iz bližnjih rek, obenem pa je lahko tudi razpokanost kamnin v teh območjih višja, saj doline dostikrat sledijo tektonskim conam. *Globina vodnjakov* nima večjega vpliva. Čeprav so razlike med nekaterimi razredi signifikantne (tabela 4, slika 3), so bolj ali manj naključne. Rezultati se skladajo z opazovanji ostalih avtorjev (LeGrand, 1967; Loiselle and Evans, 1995). Čeprav se naj bi z globino vodnjakov njihova izdatnost povečevala, obstaja tudi efekt, ki izdatnost zmanjšuje, saj se število povezanih vodonosnih razpok z globino manjša, toda ta efekt je opazen šele pri vodnjakih, globokih več tisoč metrov. Večina vodnjakov, vključenih v to študijo, je plitvejša od 300 m in v teh globinah so razpoke porazdeljene približno enakomerno po celotni globini, kar najverjetneje povzroča nesignifikantne razlike med razredi. Ali je *vodnjak popoln ali nepopoln*, prav tako ne vpliva bistveno na analizirane parametre, saj so vsi M-W in t-testi nesignifikantni (tabela 5). Vrednosti so za transmisivnost, specifično izdatnost in maksimalne pretoke višje pri nepopolnih vodnjakih, kar je v nasprotju z oceno, da so popolni vodnjaki izdatnejši, ker je z njimi možno zajeti več vodonosnega sloja (Kruseman and de Ridder, 1994). Neznačilne razlike med razredoma nastanejo skoraj zagotovo zaradi dejstva, da nepopolni vodnjaki niso izvrtani do podlage prav zato, ker že prej zajamejo zadosten del izdatnega vodonosnika in se vrtanje takrat ustavi. Zato so taki nepopolni vodnjaki po izdatnosti primerljivi s popolnimi in razlik med razredi ni.

Transmisivnost in koeficient prepustnosti sta pridobljena iz hidrogeoloških poročil, kjer sta izračunana preko Cooper-Jacobove ter Theisove metode, ki pa nista vedno primerni za karakterizacijo kraško-razpoklinskih vodonosnikov (Verbovšek, 2005). Uporaba ustreznih metod bi zato omogočila bolj poglobljeno analizo rezultatov, obenem pa bi bilo v nadaljnje primerno analizirati tudi vplive dodatnih faktorjev, npr. bližino tektonskih elementov, petroloških lastnosti kamnin ter ostalih tehničnih lastnosti vodnjakov. V članku so namreč zajeti le nekateri faktorji, ki pomembno vplivajo na hidravlične parametre, pri načrtovanju in izgradnji vodnjakov pa bi bilo potrebno upoštevati čim več tako geoloških vplivov, pa tudi značilnosti lokacije in način izvedbe.

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