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**FEASIBILITY ANALYSIS OF GROUNDWATER ABSTRACTION FOR GAS SHALE FRACTURING
IN THE LUBLIN BASIN (EASTERN POLAND)****OCENA MOŻLIWOŚCI POBORU WÓD PODZIEMNYCH DO SZCZELINOWANIA ŁUPKÓW
GAZONOŚNYCH W BASENIE LUBELSKIM (WSCHODNIA POLSKA)**

Natural gas extraction from shale rock necessitates hydraulic fracturing of rocks, which involves large amounts of fracture fluids made of 90.5% of water. The authors focus on feasibility of groundwater abstraction for the purpose of applying fracture fluids in wells of the Lublin Basin – area of perspective unconventional gas exploitation from the Ordovician and the Silurian shales. These data refer to the expected specific capacity of wells abstracting groundwater from main useful aquifers. Specific capacity of a well (q) belongs to high-certainty empirical parameters, characterizing water-bearing capacity of rocks at a regional scale. The spatial evaluation of q was based on respective data coming from 7 sheets of the Hydrogeological Map of Poland (scale 1:200,000) covering research area. Specific capacity q was calculated for wells abstracting water from the Upper Cretaceous, Tertiary and Quaternary aquifers in areas presented on particular sheets of the map. Authors determined the variability distribution and the cumulative probability plots of q values, indicating a range which corresponded to a sum of standard deviation (SD) above and below median (\bar{X}), i.e. $\bar{X} \pm 1SD$. On the total the interval included 68.2% of data. The results reveal that $0.6 \leq q \leq 40 \text{ m}^3\text{h}^{-1}$ per 1 meter of drawdown for the Upper Cretaceous rocks in the eastern part of the area, and $1.1 \leq q \leq 110 \text{ m}^3\text{h}^{-1}$ per 1 meter in the western part, being a result of more intense fracturing and fissuring. Owing to the scarcity of data, q values of wells screened at the Tertiary and Quaternary aquifers are given jointly for the whole area: $0.8 \leq q \leq 20$ and $1.0 \leq q \leq 10 \text{ m}^3\text{h}^{-1}$ per 1 meter, respectively. The obtained specific capacities are high. When the wells are properly designed, their discharges may reach about ca. $100 \text{ m}^3\text{h}^{-1}$.

Keywords: groundwater, water supply, hydraulic fracturing, water-bearing capacity, specific capacity, Lublin Cretaceous, Lublin Basin, shale gas

Eksploatacja gazu ziemnego ze skał łupkowych wiąże się z wykonaniem w każdym poziomym odcinku otworu wielu zabiegów hydraulicznego szczelinowania skał. Zabiegi te realizowane są przy wykorzystaniu dużych ilości cieczy szczelinujących, które w 90.5% składają się z wody, 9.0% piasku

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podszkockowego (proppant) oraz 0.5% różnych substancji chemicznych, niezbędnych do utrzymania właściwych parametrów technologicznych cieczy. Zapotrzebowanie na wodę do szczelinowania wzrasta wraz ze zwiększeniem zwięzłości i głębokości zalegania łupków gazonośnych. W związku z tym właściciele koncesji na eksploatację gazu ze skał łupkowych oczekują informacji o możliwościach poboru wód podziemnych w celu szczelinowania.

W pracy przedstawiono ocenę realnych możliwości poboru wód podziemnych do przygotowania cieczy szczelinujących dla otworów eksploatacyjnych gazu niekonwencjonalnego w obszarze basenu lubelskiego, będącego rejonem perspektywicznej eksploatacji gazu z łupków ordowiku i syluru (dolny paleozoik). Możliwości poboru wody zbadano na podstawie oczekiwanych wydajności jednostkowych studni ujmujących wody głównego użytkowego poziomu wodonośnego (GUPW) w rejonie badań. GUPW na przeważającej części tego obszaru związany jest ze skałami górnej kredy – spękany marglami, kredą, opokami, wapieniami i gezami, a także utworami czwartorzędu i trzeciorzęd. Znajomość wartości wydatku jednostkowego umożliwi zaprojektowanie ujęcia stosownie do określonych potrzeb. Witeczak *et al.* (1999) proponują przyjęcie wydatku jednostkowego studni (q), jako obiektywnej danej empirycznej cechującej się wysokim wskaźnikiem pewności, w celu charakterystyki wodonośności poziomów wodonośnych w skali regionalnej.

Przestrzenną ocenę wartości q oparto na danych zestawionych w 7 arkuszach Mapy hydrogeologicznej Polski w skali 1:200,000 (MHP). Dane dotyczyły q uzyskiwanych przy określonych maksymalnych depresjach poziomu wody. Obliczono q studni ujmujących wodę z GUPW w formacjach kredy górnej, trzeciorzęd i czwartorzędu, w granicach obszarów arkuszy MHP lub ich części znajdujących się w zasięgu obszaru badań (Fig. 1). Zanalizowano rozkłady zmienności i skumulowanej gęstości prawdopodobieństwa w celu uzyskania odpowiednich zakresów zmienności wartości q studni ujmujących wodę z badanych trzech formacji litostratygraficznych (Fig. 2, 3). Wyróżniono na wykresach zakres równy sumie jednego odchylenia standardowego (SD) powyżej i poniżej wartości mediany (\bar{X}), czyli $\bar{X} \pm 1SD$. W tym przedziale zawiera się po 34.1% danych o wartościach odpowiednio: większych i mniejszych od mediany; łącznie przedział zawiera 68.2% danych. Na będących źródłem danych arkuszach MHP obejmujących obszar badań, ilość danych dotyczących studni ujmujących wodę z utworów czwartorzędu i trzeciorzędu zazwyczaj jest mniejsza niż 30. Wykonano więc zestawienie q także dla danych skumulowanych w odniesieniu do poszczególnych poziomów litostratygraficznych (Fig. 3b).

Uzyskane wyniki w odniesieniu do skał kredy górnej wskazują, że analizowany obszar dzieli się na bardziej wodonośną część położoną na zachód od rzeki Wieprz, tj. w granicach arkuszy „Łuków”, „Lublin”, „Rzeszów” oraz słabiej wodonośną część położoną na wschód od tej rzeki, czyli w obszarach arkuszy „Włodawa”, „Chełm” i „Tomaszów Lubelski”. W zakresie $\bar{X} \pm 1SD$ w strefach występowania margli ilastych i kredy piaszczystej (część wschodnia obszaru) q zawierają się w przedziale $0.6 \leq q \leq 40 \text{ m}^3\text{h}^{-1}$ na 1 m depresji. W rejonach występowania opok, gez, margli i wapieni (część zachodnia) q jest w przedziale $1.1 \leq q \leq 110 \text{ m}^3\text{h}^{-1}$ na 1 m. Wartości q studni zafiltrowanych w utworach trzeciorzęd i czwartorzędu, za względu na małą ilość danych analizowano łącznie dla całego obszaru badań i stwierdzono, że zawierają się w przedziale $\bar{X} \pm 1SD$ odpowiednio $0.8 \leq q \leq 20 \text{ m}^3\text{h}^{-1}$ na 1 m oraz $1.0 \leq q \leq 10 \text{ m}^3\text{h}^{-1}$ na 1 m.

Oprócz zmienności litologicznej, rozkład zmienności q w skali regionalnej w danym poziomie litostratygraficznym ma charakter lognormalny. Projektując studnie ujmujące wodę w obszarze badań z utworów kredy górnej zaleca się przyjmowanie wartości dolnej granicy przedziału zmienności $\bar{X} \pm 1SD$ zestawionych w Tabeli 1. Projektując ujęcia wody z utworów trzeciorzęd lub czwartorzędu, z uwagi na małą liczbę danych dotyczących tych poziomów w zasięgach arkuszy będących źródłem danych, zaleca się przyjmowanie wartości dolnej granicy przedziału zmienności określonego dla danych połączonych ze wszystkich arkuszy (Tabela 1). Obliczenie przewidywanej wielkości poboru wód podziemnych pojedynczą studnią w granicach koncesji na eksploatację gazu łupkowego w Basenie Lubelskim można wykonywać na podstawie wartości q przedstawionych w pracy. Stwierdzone w wyniku badań wartości q są wysokie i gwarantują, przy prawidłowym zaprojektowaniu lokalizacji i budowy studni, uzyskiwanie wydajności od kilkudziesięciu do ponad $100 \text{ m}^3\text{h}^{-1}$ wody.

Słowa kluczowe: wody podziemne, zaopatrzenie w wodę, szczelinowanie skał, wodonośność, wydajność jednostkowa, kreda lubelska, Basen Lubelski, gaz łupkowy

1. Introduction

Natural gas prospecting in shales is realized through normal-diameter and multi-floor wells, up to a few thousand meters of depth. Drilling technologies used for this purpose basically do not much differ from the ones used in conventional hydrocarbon fields, except for more numerous hydraulic fracturing operations and high-density drilling network (Macuda, 2010).

Hydraulic fracturing of shale rocks is a technique thanks to which gas present in the rock pores can be extracted. When the drilling is complete, large amounts of fracture fluid suitable prepared and containing sand as proppant are injected to the selected interval with a horizontal well section to fracture it and prevent the fractures from closing (Siemek & Nagy, 2012).

In the industrial practice it is 10 to 15 fracturing operations which are performed on a horizontal section ca. 1,500-2,000 m long. From about 8,000 to 30,000 m³ of water and 500 to 2,500 Mg proppant are used for fracturing operation in one horizontal well (GWPC & ALL Consulting, 2009). As a consequence of this activity the fractures propagate in shales 200 to 300 m off the well.

One of the most perspective natural gas extraction areas in Poland is the Lublin Basin (Nagy & Siemek, 2011) comprising the Lower Paleozoic (the Ordovician and the Silurian) shales which is actually explored in detail (Kiersnowski & Dyrka, 2013). Therefore, it is extremely important to precede drilling operations with an earlier assessment of water-bearing capacity of major useful aquifers in this area and establish real possibilities regarding groundwater abstraction for fracturing purposes. This knowledge is essential for the holders for shale gas exploitation concessions as on this basis they can optimize water management in the drilling area in advance.

2. Hydrogeological characteristic of the area

The predominant part of research area occupies the main useful aquifer (MUA) related to the Upper Cretaceous rocks: fractured marls, chalk, limestones and gaizes. In such rocks the conductivity and groundwater flow depend on fractures. In this case the fissuring changes from 0.15 to 7.9% (Kleczkowski ed., 1990). Typically for the Lublin Cretaceous formation, the top part is discontinuously watered, with zones of low permeable and unfractured rocks, and perched groundwater above. The difference between water table of perched groundwater and the underlying groundwater level may exceed even 20 m (Kleczkowski ed., 1990; Paczyński & Sadurski eds., 2007).

The water-bearing capacity of carbonate rocks in the analyzed area is diversified not only lithologically, but also vertically and horizontally. This is additionally reinforced by the degree of tectonic involvement and the increased fracturing of the strata in the fault zones (Woźnicka, 2005).

The depth of active groundwater exchange depends on the depth range of the fractures. Krajewski & Motyka (1999) found that in the Lublin Cretaceous formation area the depth of high permeable rocks, where the hydraulic conductivity $k > 1 \cdot 10^{-5} \text{ m} \cdot \text{s}^{-1}$, is limited to 100 m in chalk and argillaceous marl, 120-130 m in marl and 150 m in gaizes and limestones. The Lublin Cretaceous rocks hydraulic conductivity varies within the following ranges: $2.4 \cdot 10^{-6}$ to $4.8 \cdot 10^{-3} \text{ m} \cdot \text{s}^{-1}$ for gaizes, marls, and $1.1 \cdot 10^{-7}$ to $5.0 \cdot 10^{-4} \text{ m} \cdot \text{s}^{-1}$ for chalk (Woźnicka, 2004). In the fault zones within river valleys hydraulic conductivity may exceed $2 \cdot 10^{-3} \text{ m} \cdot \text{s}^{-1}$ in massive limestones and gaizes, however only amounts to $9 \cdot 10^{-4} \text{ m} \cdot \text{s}^{-1}$ about 400 m off the fault, and even less in the more distant areas (Krajewski & Motyka, 1999).

The groundwater table occurs at a small depth in the river valleys, unlike hill tops where it can be found at over 80 m of depth. Therefore, at a similar thickness of fractured and cracked rocks part, the saturated zone thickness is smaller in the water divide areas and higher within river valleys. Consequently, the transmissivity of the aquifer is lower on hills and higher in valleys, where $100 < T < 1,000 \text{ m}^2\text{d}^{-1}$ (Woźnicka 2004, 2005; Paczyński & Sadurski, 2007).

The permeable Quaternary sediments fill out depressions cutting the roof part of the Upper Cretaceous rocks to a depth of 50-150 m creating a common Quaternary-Cretaceous MUA. Sands and gravels play an important role also in the bigger rivers valleys (i.e., Wieprz, Bug and Por), where the thickness reaches up to 40 m (Malinowski, ed., 1991).

The simplified stratigraphic ranges of the MUA presented in Fig. 1 were obtained by analyzing ranges of hydrogeological units delineated on the Hydrogeological Map of Poland (HMP) in scale 1:200,000, performed by the Polish Geological Institute (see: source materials). The boundary of the shale gas fields exploration concession area in the Lublin Basin was determined on the basis of source materials stored at the Ministry of Environmental Protection (PGI & ME, 2013).

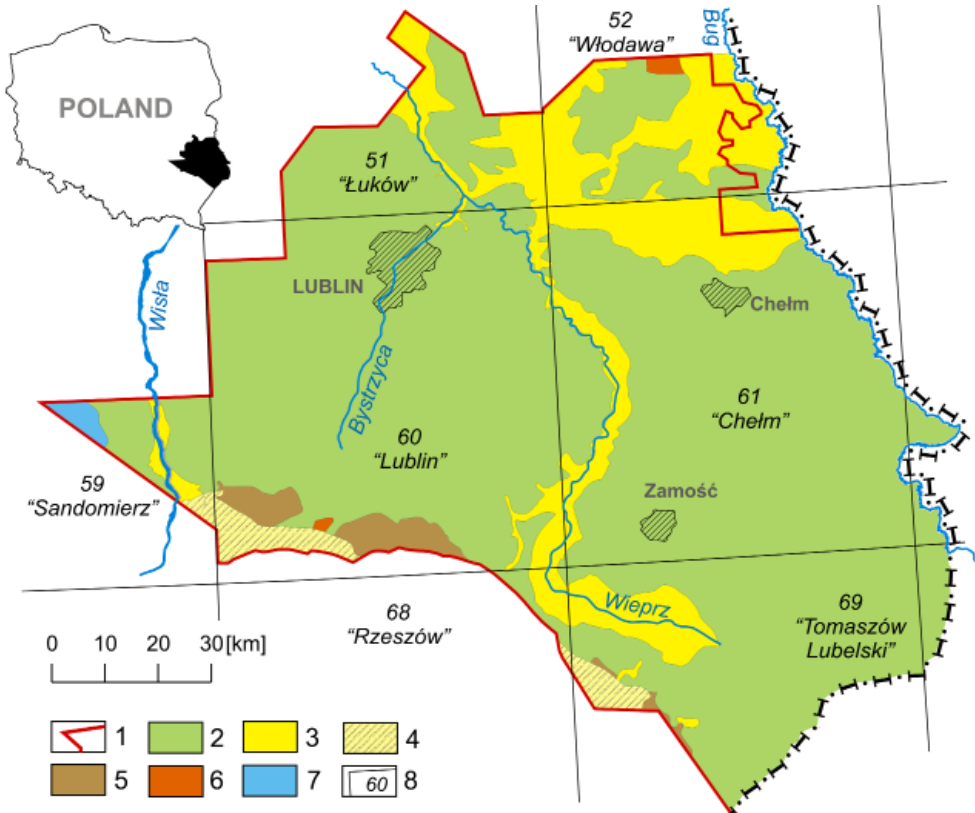


Fig. 1. Range of the main useful aquifer (MUA) within the Lublin Basin concession area. 1 – concession area, according to the condition as of 30 April 2013, based on: PGI & ME (2013), 2-7 – MUA in formations: (2) Upper Cretaceous, (3) Upper Cretaceous and Quaternary, (4) Quaternary, (5) Upper Cretaceous and Tertiary, (6) Tertiary, (7) Upper Jurassic, 8 – boundary, number and name of HMP sheet 1:200,000

The Lublin Cretaceous abounds in groundwater of $\text{HCO}_3\text{-Ca}$ or $\text{HCO}_3\text{-Ca-Mg}$ type with mineralization ranging from 200 to 600 (900) $\text{mg} \cdot \text{dm}^{-3}$, on average about 450 $\text{mg} \cdot \text{dm}^{-3}$, and pH from 6.5 to 8.15. These are medium-hard or hard groundwater. Their total hardness ranges between 170 and 837 $\text{mg} \cdot \text{dm}^{-3}$, with the highest values observed in the valley areas (Paczyński & Sadurski eds., 2007). It is also valley areas where higher concentrations of SO_4 , Cl, Fe and Mn are observed. Groundwater can be used either without prior treatment or only after iron and manganese have been removed. In the SW part of the analyzed area, in the Sanna River catchment, the nitrates contamination is higher therefore water may need treatment (Paczyński & Sadurski eds., 2007).

3. Method of spatial evaluation of MUA water-bearing capacity

An objective definition of transmissivity and water-bearing capacity of larger hydrogeological structures should be based on empirical information of relatively high certainty value. Witczak et al. (1999) and Duda & Paszkiewicz (2007) propose the specific capacity of a well to characterize the water-bearing capacity of aquifers on regional scale. The knowledge of a specific capacity value will be useful while designing intake adjusted to the user's particular demand.

The spatial evaluation of well's specific capacities within the Lublin Basin concession area was based on data in denotations listed on seven sheets of the HMP in scale 1:200,000 (see the list of source materials). The data referred to the well discharge obtained at given maximum groundwater level drawdown. On this basis the specific capacities were obtained for wells which were abstracting water from the MUA in the Upper Cretaceous, Tertiary and Quaternary formations, within areas represented in the HMP particular sheets or their parts within the study area range. The boundaries of sheets and range of the concession area are presented in Fig. 1.

The regional variability of parameters characterizing hydrogeological units is considerable for fracture-porous media due to the internal diversity existing at a small distance between rock mass blocks and the fractures system. In such a case the description of selected hydrogeological units on the basis of averaged parameters values should be also indicative of the variability's character, otherwise it is insufficient. For obtaining proper ranges of specific capacities of a wells abstracting water from three lithostratigraphic formations in the analyzed area, their the variability distribution and cumulative probability were investigated. The interval equal to a sum of standard deviation (SD) above and below median (\bar{X}), i.e. $\bar{X} \pm 1SD$ was specified for them. This interval covers a total of 68.2% of data: 34.1% of data are higher, and 34.1% are lower than the median. This interval was considered to be sufficiently informative of the analyzed parameter variability in relation to median (\bar{X}), i.e. a value of 50% probability.

The specific capacity has a lognormal variability distribution, similar to the hydraulic conductivity of rocks or transmissivity of the aquifer. Hence the specific capacity variability was plotted in a logarithmic scale on the chart. The boundary values of variability interval related with the range of $\bar{X} \pm 1SD$ were read out from the logarithmic scale with accuracy provided by the graph. Accordingly, the values were approximate. Nonetheless, the error connected with the graphical evaluation was assumed to be negligible due to the large variability range of the analyzed parameter. Within the analyzed interval the variability range equals to two, sometimes to three orders of magnitude.

4. Results and discussion

The probability of obtaining relevant specific capacities of wells discharging water from three lithostratigraphic formations, i.e. Upper Cretaceous, Tertiary and Quaternary, is plotted in Figs. 2 and 3. As far as statistical analysis goes, the evaluation of a random variable based on less than 30 data has on overview value only. The number of data referring to wells screened in the Quaternary and particularly Tertiary strata, usually does not exceed thirty on each of particular the HMP sheets covering the researched area. Therefore the specific capacities were plotted for cumulative data in particular three lithostratigraphic formations, too (Fig. 3b).

The obtained results for the Upper Cretaceous rocks reveal that the analyzed area can be divided to a high water-bearing part west off the Wieprz River, i.e. within „Łuków”, „Lublin”, „Rzeszów” sheets, and low water-bearing part east off the Wieprz River, i.e. within „Włodawa”, „Chełm” and „Tomaszów Lubelski” sheets. This is due to the fact that gaizes and limestones dominating in the geological profile of the Upper Cretaceous strata in the western and central part of the study area are harder rocks than marls and chalk occurring in the eastern part (Paczyński & Sadurski, eds., 2007).

The specific capacities obtained in the areas of occurrence argillaceous marls and chalk range from 0.6 to 40 m³h⁻¹ per 1 meter of drawdown in well within interval $\bar{X} \pm 1SD$. In this interval for gaizes, marls and limestones the specific capacities values oscillate between 1.1 and 110 m³h⁻¹ per 1 meter, being a result of increased conductivity caused by more intense fracturing. Rivers valleys and faults zones causing a greater degree of fracturing of the Upper Cretaceous rocks are most perspective zones for water intakes in the analyzed area.

Due to the scarcity of data, the specific capacities of particular wells screened in the Tertiary and Quaternary aquifers are determined jointly for the entire research area. Within interval $\bar{X} \pm 1SD$, ranging from 0.8 to 20 m³h⁻¹ per 1 meter and 1.0 to 10 m³h⁻¹ per 1 meter, respectively.

Here looms a problem related to the choice of a correct value to be assumed at the stage of well designing in the Lublin Basin concession area. Such value should guarantee with high degree of probability that predefined amounts of water will be abstracted. The deviations from median value (\bar{X}) are too large in the analyzed area therefore their determining at the designing level is not recommended. Besides, apart from the lithological variability, the specific capacity of a well has a variability distribution of lognormal character on a regional scale. Therefore, assuming a median will be burdened with a significant error in reference to the actual value which can be considerably lower than the assumed one.

When designing wells abstracting water from the Upper Cretaceous rocks within the area covered by specific HMP sheets (scale of 1:200,000), the lower limit values of variability interval contained in Table 1 are recommended. When designing water intake from the Tertiary and Quaternary aquifers, the lower limit values of variability interval determined for cumulative data from all analyzed sheets of HMP covering the research area, i.e from lowermost row in Table 1, should be assumed. This is due to the scarcity of information about these aquifers within borders of particular sheets of the Lublin Basin area. In this approach the actual specific capacity of a well will be with a probability of 83% higher or equal to the value assumed for a given well in the project. This probability level suffices to guarantee a long operation of a well with the assumed yield.

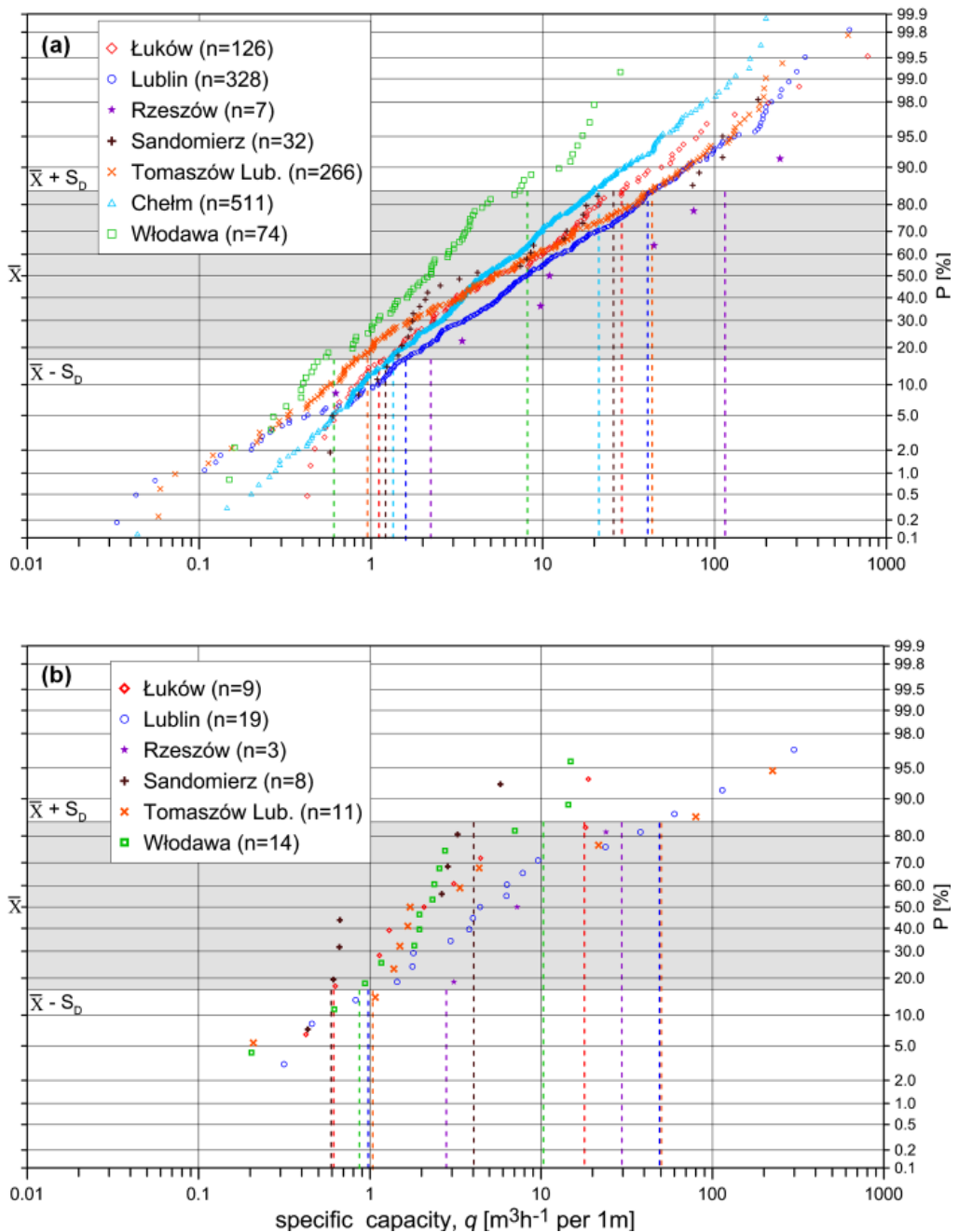


Fig. 2. Variability of specific capacity of wells abstracting water from aquifer (a) Upper Cretaceous, (b) Tertiary, divided into areas covered by given sheets HMP 1:200,000. *Łuków* – map sheet name, n – number of data, P – probability, \bar{X} – median, S_D – standard deviation

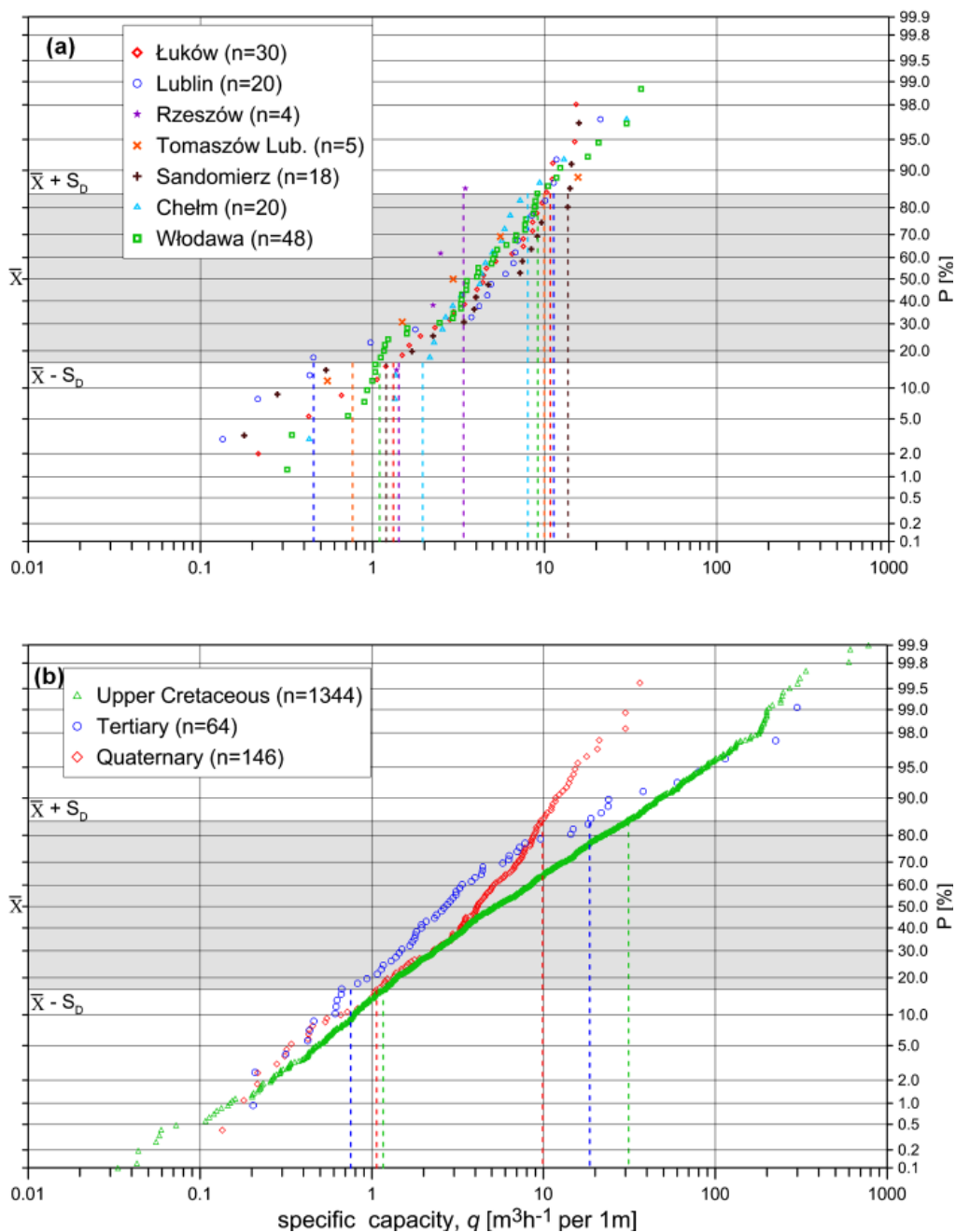


Fig. 3. Variability of specific capacity of wells abstracting water from (a) Quaternary aquifer, divided into areas covered by given sheets HMP 1:200,000. (b) main aquifer – data accumulated in particular lithostratigraphic formations. *Łuków* – map sheet name, n – number of data, P – probability, \bar{X} – median, S_D – standard deviation

TABLE 1

Variability of specific capacity of wells abstracting groundwater from aquifers in concession area of Lublin Basin, values within interval $\bar{X} \pm 1SD$

Number and name of HMP sheet	Upper Cretaceous	Tertiary	Quaternary
	m ³ h ⁻¹ per 1m of drawdown		
51 Łuków	1.1-30	0.6-18	1.2-11
52 Włodawa	0.6-8	0.9-10	1.05-9
59 Sandomierz	1.5-30	0.6-4	1.1-13
60 Lublin	1.6-40	1.0-50	0.45-11
61 Chełm	1.4-20	absent	2.0-8
68 Rzeszów	2.0-110	2.8-30	1.3-33
69 Tomaszów Lubelski	0.9-40	1.0-50	0.8-10
Total data	1.0-30	0.8-20	1.0-10

5. Conclusions

The main useful aquifer in the predominant part of the Lower Paleozoic Lublin Basin is related to the Upper Cretaceous rocks developed in the form of fissured marls, chalk, limestones and gaises. The water-bearing capacity of these rocks, characterized by the specific capacity of a wells, is generally moderate and high, though diversifies lithologically and spatially. The specific capacity gradually decreases towards the eastern border of the research area with the changing lithofacies.

The proposed method proved to be fit for an approximated spatial evaluation of specific capacity of a wells. The expected abstraction of groundwater with a single well within the shale gas concession area can be assessed on the basis of specific capacities of a wells presented in this paper. Determined specific capacities in the analyzed area guarantee the yield of tens to over 100 m³h⁻¹ of water, provided the location was selected properly and the well construction designed and performed correctly. The planned water wells should be localized mainly in the river valleys or directly near documented faults, and their depth should not exceed 60-80 m.

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