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RESEARCH IN ABANDONED WELL QUESTIONS THE PRACTICE OR WELL REPRESENTATIVITY CRITERIA USED IN SELECTING FOR GROUNDWATER MONITORING SITES

BADANIA W PORZUCONYM OTWORZE KWESTIONUJĄ PRAKTYKĘ I/LUB KRYTERIA REPREZENTATYWNOŚCI STOSOWANE PRZY WYBORZE PUNKTÓW MONITORINGU WÓD PODZIEMNYCH

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Abstract. The object of research is well No. 5p (UE_ID: PL06G110_004) located in Sokołowsko (the Sudetes, SW Poland). Since completing the well in 1980, it has never been included in water services due to poor water quality, but simply abandoned. The abandonment, lasting already 32 years, has established an unintended long-term experiment in the well. Of the four screened water-bearing horizons, two lower ones run more pressurized sulphate mineral water, which has generated a permanent upward flow within the well and pollution of fresh water in upper ones. The consequences are much wider, as the combination of hydraulic and geochemical settings formed an in-hole natural laboratory in which bio-geochemical processes affect the water quality and the contamination by hydrocarbons enhanced by human activity. The well should ultimately be closed down. Because the well has been included in the national monitoring network for over 20 years, these results also impel to postulate for establishing: 1) a more strong procedure for testing the representativity of observation points in the monitoring network, 2) a revision programme for already existing points, and 3) amendments to the regulations to explicitly solve the case of "orphans" due to the risk they may cause.

Key words: abandoned water well, in-well geochemical environment evolution, well screen clogging, groundwater monitoring, credibility of observation well, Poland.

Abstrakt. Przedmiotem badań jest otwór studzienny nr 5p (UE_ID: PL06G110_004) położony w Sokołowsku (Sudety). Od wykonania w 1980 roku, z uwagi na złą jakość wody, nigdy nie włączono go do sieci wodociągowej, i w konsekwencji porzucono. Brak eksploatacji przez 32 lata spowodował stworzenie się w nim warunków do niezamierzonego, długotrwałego eksperymentu. Z ujętych w otworze wspólnie czterech stref wodonośnych, dwie dolne prowadzą wody mineralne pod większym ciśnieniem, co powoduje ich stały pionowy przepływ w otworze i zanieczyszczenie wyżej ległych wód zwykłych. Hydrauliczne i geochemiczne warunki w studni sprzyjają procesom biogeochemicznym wpływającym na jakość wody i wzbudzone przez działalność człowieka zanieczyszczenie węglowodorami. Otwór powinien być niezwłocznie zlikwidowany. Z uwagi na to, że studnia od około 20 lat jest w sieci monitoringu krajowego, wyniki te skłaniają również do postulowania ustanowienia: 1) skutecznej procedury oceny reprezentatywności punktów obserwacyjnych w sieci monitoringu, 2) programu rewizji istniejących punktów, oraz 3) nowelizacji regulacji w celu rozwiązania problemu „osieroconych" otworów, ze względu na zagrożenia jakie one stwarzają.

Słowa kluczowe: porzucony otwór studzienny, geochemiczna ewolucja środowiska studziennego, kolmatacja filtru, monitoring wód podziemnych, wiarygodność punktu obserwacyjnego, Polska.

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INTRODUCTION

The object of research is well No. 5p (MONBADA No. 1183; UE_ID: PL06G110_004; Groundwater Body No. 110) located in Sokołowsko (the Sudetes, SW Poland) (Fig. 1), the presumptive source of water supply to the town of Wałbrzych. Because the well was completed in 1980 and the investigations were oriented on water resource assessment, it has never been included in water services due to poor water quality, and simply abandoned. Despite the poor water quality in terms of drinking water standards, chemical composition of mineral water attracted the interest on this well again.

Research was made to assess the balneological potential of mineral water, and included a wide set of geochemical examinations (Dobrzyński, 2009). Preliminary goal of the research was to identify the origin of water chemistry and water age, to explain the spatial pattern of water chemistry, and to examine the technical condition of the well. The study results displayed changes in geochemical characteristics of in-well water, which were not predicted before. Since 2000, the research has focused on periodically repeated water column profiling and chemical analyses, which confirmed the

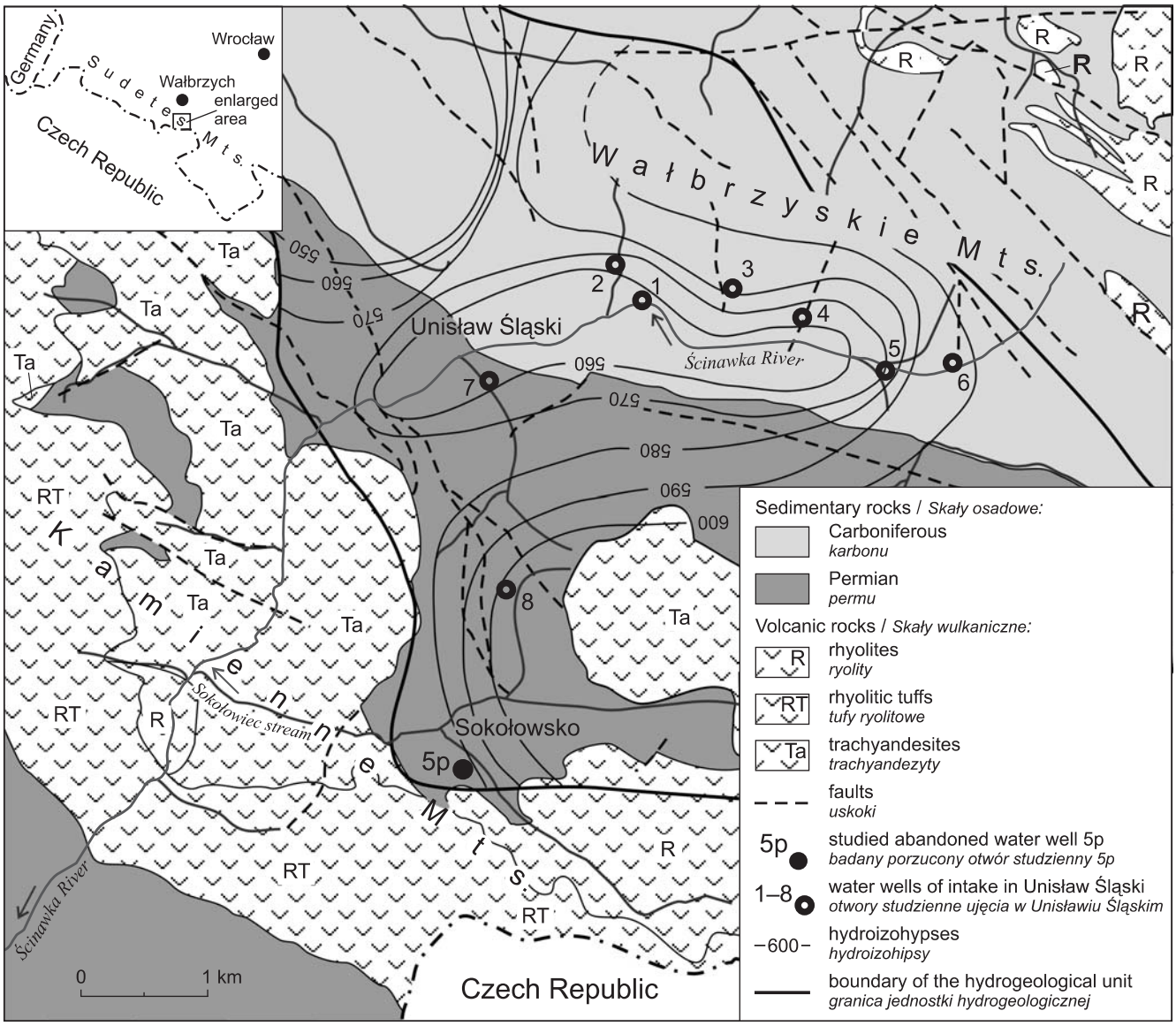

Fig. 1. Location of the studied water well 5p (after Dobrzyński, 2009; modified)

Hydroizohypses and limit of hydrogeological unit after Wojtkowiak (2000, 2002)

Lokalizacja badanego otworu studziennego 5p (wg Dobrzyńskiego, 2009; zmienione)

Hydroizohipsy i granica jednostki hydrogeologicznej według Wojtkowiaka (2000, 2002)

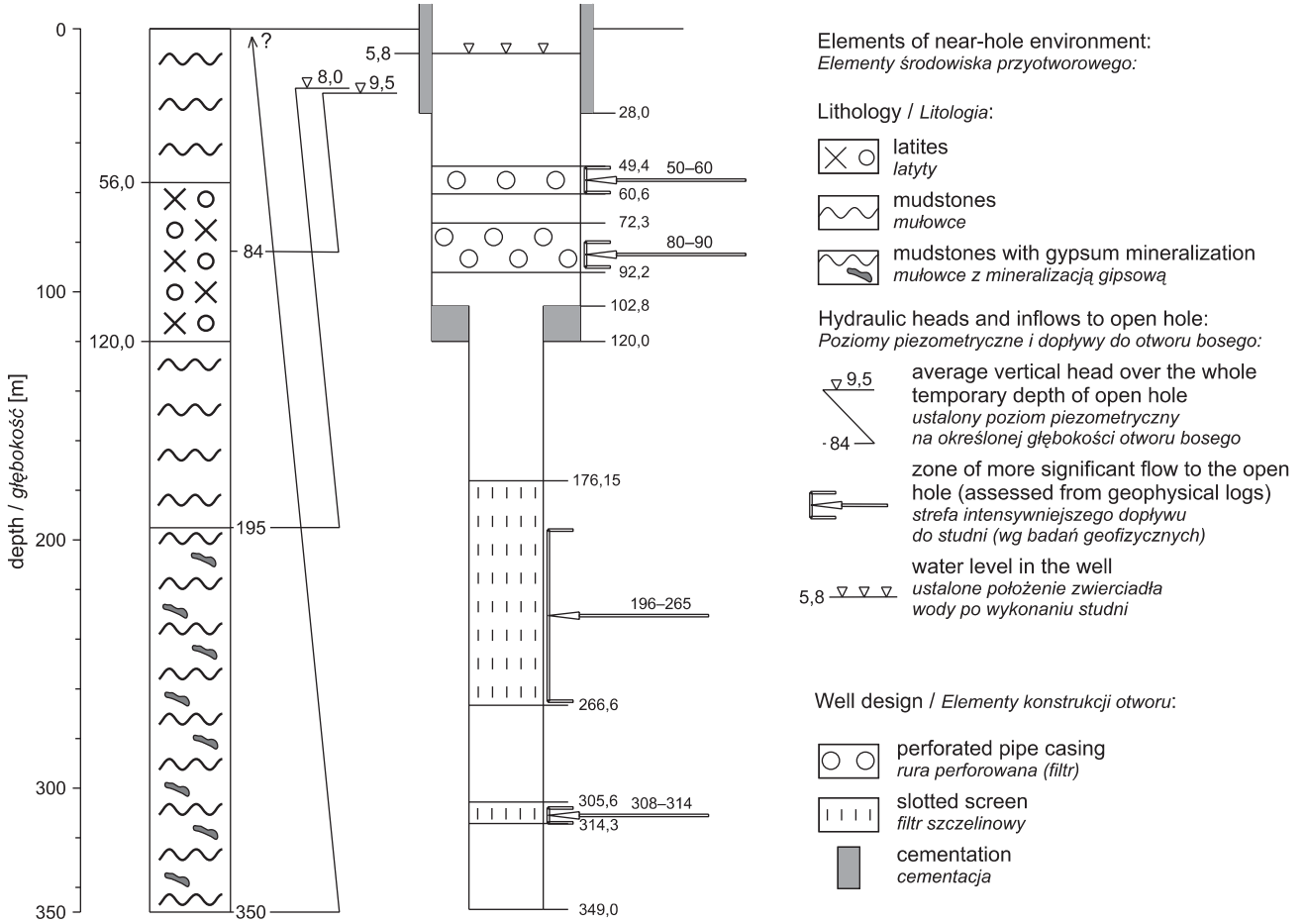

Fig. 2. Schematic diagram of initial near-hole environment and design of well 5p (mainly after Dąbrowski and Szafranek, 1982; Szafranek *et al.*, 1986)

Schemat pierwotnych przyotworowych warunków środowiskowych i konstrukcji studni 5p (głównie na podstawie Dąbrowski, Szafranek, 1982; Szafranek i in., 1986)

progress in changes of the in-well water environment. These results were the reason for extending the research by geomicrobiological examinations (Borkowski *et al*., 2013). The up-to-date research results raise concerns of the situation caused by the well 5p. Primarily, an unplugged abandoned well, such as "orphan", becomes an artificial water conduit. It provides hydraulic communication between fresh and saline water bodies (Fig. 2), leading to uncontrolled and unconsidered contamination of fresh water by saline intrusion. Another concern relates to formal aspects if they admit to safe abandonment of the hole in unplanned manner and rank it to the position of observation point in the monitoring network. It is very important, as the well 5p has been functioning for almost 20 years as an observation point in chemical and transboundary monitoring (http://www.psh.gov.pl). In this particular case, the selection was made for the study area that belongs to the upper part of the Ścinawka River transboundary catchment (in the territory of Poland and Czech Republic). It seems that only the geographical location decided about including this well to the nationwide monitoring network and transboundary projects, serving to reports required under the Water Framework Directive (WFD).

This case study of "orphan" is an attempt to highlight the consequences of 32-year abandonment, which established an unintended long-term experiment in the well, and in fact, an in-hole natural laboratory.

HYDROGEOLOGICAL SETTING

In the study area, the bedrocks are Carboniferous–Permian terrestrial clastic rocks (mainly conglomerates, sandstones and mudstones). In the S part of the area, Permian volcanogenic rocks occur. Groundwater flow within both the unconfined and confined parts of the system is predominantly through fissures. The fresh groundwater system has an irregular

Table 1

Selected physico-chemical characteristics of water from the well 5p (after authors' studies)

Wybrane parametry fizyczno-chemiczne wody z otworu 5p (według badań autorów)

Parameter	Mineral water[1]	In-well water[2]			
	(VIII.2000)	(IX.2009, 35 m b.l.s.)	(IX.2009, 50 m b.l.s.)	(X.2012, 38 m b.l.s.)	(X.2012, 55 m b.l.s.)
pH	7.71	9.76	7.81	9.70	8.34
SEC[3] / PEW[3] [µS/cm]	1920	3070	3420	3030	3260
E_H measured [mV]	–167	–24	83	–72	–162
H_2S [mg/L]	0.44	1.00	1.30	0.60	0.85
O_2 [mg/L]	0.60	3.00	3.07	0.24	0.25
SO_4 [mg/L]	1061	1500	1680	920	1020
F [mg/L]	<0.10	0.95	0.96	1.00	1.45
Ca [mg/L]	305.9	220.0	308.9	281.8	302.9
Fe [mg/L]	0.25	0.054	0.033	0.097	0.078
As [mg/L]	0.130	<0.006	<0.006	0.011	0.022
Benzene [µg/L]	n.a.	5.1	10	n.a.	n.a.
BTEX (sum) [µg/L]	n.a.	178	325	n.a.	n.a.
Aliphatic hydrocarbons (sum) [mg/L]	n.a.	0.07–0.10	0.10	n.a.	n.a.
PAH (WWA) (sum) [µg/L]	n.a.	49	130	n.a.	n.a.

[1] sampled by using sampler during pumping test at the depth of 95 m b.l.s.; opróbowane podczas pompowania przy użyciu próbnika na głębokości 95 m p.p.t.
[2] sampled by using sampler in quasi-stagnant in-well water column; opróbowane przy użyciu próbnika w quasi-stagnującej kolumnie wody w otworze
[3] specific electric conductivity; przewodność elektrolityczna właściwa
n.a. – not analysed; nie badane

geometry and is relatively thin. Geochemical investigations (Dobrzyński, 2009) revealed that the hydrogeological system is chemically and isotopically diversified. These features also have a horizontal N–S orientation with a southward increase in: 1) salinity and chemical character from Ca-HCO_3-SO_4 type to Ca-Na-SO_4 type (mineral water in well 5p), 2) mean tritium-age (from 10–20 to 100–200 years). The sulphate mineral water from well 5p, with radiocarbon age of about 5.9 ka BP, represents the most chemically evolved groundwater found in the area. The diversity is caused by water mixing, conditioned by both lithological and tectonic factors (op.cit.).

The abandonment of well 5p made it a part of hydrogeological setting, as the borehole disturbed the natural environment of this area. The well construction includes four screen sections opening confined water-bearing horizons, which differ in terms of both pressure and chemical composition. The hydrodynamic conditions in the well are typical for a discharge area. There is a higher hydraulic head in deeper horizons (Fig. 2). Figure 2 shows initial conditions in the well. The two upper horizons yield fresh water, whereas the two deeper ones yield mineral water. The borehole, bottomed at the depth of 350 m, was made by a rotary flush boring technique, mostly in mudstones, and therefore, the increasing well efficiency actions were applied afterwards. The screens were installed along four confined water-bearing zones, separated by aquitards. The upper part of the well, down to 102.8 m b.s.l., is 14 inches in diameter, whereas the lower one is 238 mm. Hydraulic contact between water-bearing zones was cut away by way of cementing (Fig. 2). Pilot pumping tests were performed when the borehole cut the next water-bearing zone, and finally, a multi-rate test to assess the well's safe yield (1980) and multiple pumping test (1985) in completed well were made. Archival chemical analyses from pumping tests after completing the well provided data only on mixed-waters, as water sampled at outflow was a resultant mixture of waters coming from all screened inflow zones. The drilling report noted that the overflow from an open hole below the lowest screened zone was 0.3 m^3/h, and the water level reached +0.25 m. At present, the hydraulic head in the well is balanced by the recharge-discharge system which maintains it at a stable position of approx. 5.8 m b.s.l. Simultaneously, the entire water column in the well is presently saline (Tab. 1). In Table 1, only the results obtained by the authors are compiled.

RESEARCH METHOD

Long-term comprehensive geochemical and hydrogeological studies have been carried out in Sokołowsko and its vicinity. Geochemical research covered (Dobrzyński, 2009; Borkowski *et al*., 2013): 1) multiple chemical analysis of groundwater (2000–2012); 2) stable isotopes (δ^2H, $\delta^{18}O$, $\delta^{13}C$, $\delta^{34}S$) in groundwater; 3) tritium and radiocarbon dating of groundwater; 4) chemical and isotopic ($\delta^{18}O$, $\delta^{13}C$, $\delta^{34}S$) composition of the most reactive minerals (carbonates, gypsum); 5) geochemical modelling of groundwater; 6) estimation of mineral reaction rates in the aquifer based on field data; 7) multiple chemical analysis of in-well water; 8) determination of organic compounds in bedrocks; 9) mineralogy of well clogging; 10) microbiological and molecular analysis of water and microbial mat from the well 5p. In-hole physico-chemical profiling was periodically repeated in years 2000–2012. The QA/QC programme applied indicated that the main solutes were investigated with a very good precision and reflect the geochemical distribution in the aquifer.

For this case study, archival data on pumping have been re-examined, recorded during: 1) pilot pumpings and hydraulic head positioning in open hole during the progress of drilling, 2) multi-rate pumping to assess the well safe yield, 3) multiple pumping to test the interference among wells made for the regional water supply project, and 4) one step pumping, connected directly with the present study, to confront the losses in well efficiency as a consequence of the abandonment time scale. The latest investigation (in 2000) included also the measurement of well depth prior to pumping, which displayed entire perviousness of the well to 329 m b.s.l., i.e. 15 metres below the lowest screen. This log record became a basic for choosing the interpretation method of all results from the above-mentioned pumping tests, as comparatively the most grounded. The method assumes that changes ongoing in the well's hydraulics do reflect in time series of Q/S (specific capacity) terms, which expresses the well's efficiency evolution, while rock mass properties remain constant. Under such constraints, a simple estimation of upward discharge and distribution of saline water intrusion rates was applied. The bases of this approach are: 1) Q/S – specific capacity already reflects the formation and actual well losses, 2) all hydraulic data acquired during the progress of drilling represent the entire profile cut at the temporary depth of hole, 3) estimates of intrusion rate distribution directly rely on records of excessive heads prevailing along apparent sections of the hole and specific capacity terms corresponding with them, 4) inflow to well is balanced by outflow from it and the flows are in the steady-state, 5) chemical characteristics of well water is always time-scale dependant according to the ratio between the volumes of intruded and pumped off water. Direct measurement of the vertical flow in the well 5p has not been performed, but an inspecting camera (in 2008) displayed a sign of flow in the well.

DISCUSSION

The hydraulics of the system intersected by the well forms a driving force for in-hole upward flow of mineral water and its intruding into the upper fresh water horizons. Abandonment of the 5p well in an unprepared way was an environmentally inappropriate action. As an "orphan", the well 5p exerted the measurable (a) in-well, (b) near-field, and (c) probable far-field consequences. The primary consequence observed in all scales is the intrusion of mineralised water into fresh water bodies (in terms of WFD – Quevauviller, 2008). In addition to the saline water intrusion into fresh water horizons, periodically repeated analyses from the well also show the appearance of new geogenic pollutants (hydrocarbons).

Monitoring studies of water quality do not include hydrocarbon determinations. At the first, the presence of hydrocarbons in water from the well was macroscopically noticed and analysed by the authors in 2009 (Tab. 1). There are indications that the hydrocarbons have a natural, geogenic origin. The equipment used for camera inspection and in-well water profiling could not pose a threat.

Terrestrial sedimentary rocks of the study area commonly contain organic matter, including also interbeds of bituminous limestones and shales. Petroleum products extracted from shale rocks sampled in the vicinity of Sokołowsko revealed the presence of alkanes as well as mono- and polycyclic aromatic hydrocarbons (Borkowski *et al*., 2013), which considerably supports the hypothesis about the geogenic origin of hydrocarbons in the groundwater.

Chemical diversity of this groundwater system is created by the mixing of modern ^3H-bearing fresh water and older mineral water (Dobrzyński, 2009), which was confirmed both by geochemical modelling and groundwater dating (Fig. 3). At the quantitative evaluation of the mixing ratio, it was taken into account that mineral water from the well 5p constitutes a mixture of pure sulphate mineral water with fresh water. In the case of deeper horizons, the percentage of the sulphate mineral water component is estimated at 65%. Mineral water is of Ca-Na-SO_4 type with pH≈7.6, TDS≈1.8–2.0 g/L, and increased levels of Mg, B, As, Fe and Sr. It owes its chemical composition to a dedolomitization process driven by gypsum dissolution. The mineral water has a key importance for understanding the system, is planned to be balneologically used, and it threatens the quality of the overlying fresh water aquifer.

The camera inspecting the well 5p in 2008 revealed adverse phenomena, like in-hole upward flow, considerable

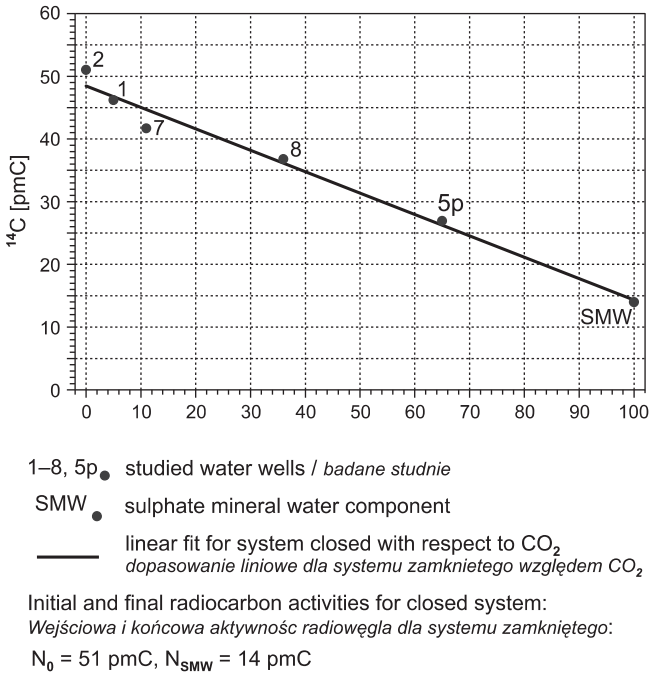

Fig. 3. Mixing curve of fresh and mineral water (after Dobrzyński, 2009, simplified)

Krzywa mieszania wód zwykłych i mineralnych (wg Dobrzyńskiego, 2009; uproszczone)

biofouling of well casing in the interval from 48 to 96 metres, and a microbial mat that fouled the entire inside of the well at a depth of 97 m. Surface of the two upper ("fresh water") screens is obstructed due to biogenic incrustation consisting mainly of Fe(II)S and $CaCO_3$ solids. Abundant microorganism communities, comprising from sulphate reducing and iron-sulphur cycle bacteria, were documented in water and the microbial mat (Borkowski et al., 2013). The biogeochemical evolution appearing in the well is driven by the water circulation, which fates the water column with water-rock interaction products, and provides bacteria with necessary substrates for metabolic activity, i.e. hydrocarbons, and SO_4^{2-} and Fe^{2+} ions. Observed consequences run rapidly at present, and ongoing bio-geochemical processes influence dramatically the water column chemistry. Development of bacteria in quasi-stagnant water caused its serious quality degradation (Tab. 1). During the period 2009–2012, changes of in-well water chemistry generally manifested in a pH and H_2S increase associated with a decrease of DIC, PO_4, and DOX, and fluctuations of TDS, E_H, and pH along the vertical section. Records of 2009 revealed contamination of in-well water by geogenic hydrocarbons (Tab. 1). The long-time intrusion of mineral water into fresh water aquifers has led to their contamination by sulphates, metals, fluorides and hydrocarbons.

The distribution of mineral water inflows back to the rock mass along the vertical cross section of the well depends on hydraulic excessive pressure exerted by more pressurized horizons identified during the hole drilling. This hydraulic control sets the overpressure of 2.2 m and 3.7 m, respectively in relation to the borehole sections of 195–176 m and 84–50 m (cf. Fig. 2). Taking into account all Q/S values calculated from pilot test pumpings in open hole (i.e. for particular sections of the hole) and results of multiple pumping and pumping test in 2000, it is found that this indicator always keeps very close to 2.4 m^3/h/1mS. On this basis, a rough guess estimates of the mineral water intrusion rates back to the rock mass are as follows: approx. up to 14–15 m^3/h as the total value (i.e. to all relatively under-pressured sections screened in the well) and approx. up to 9 m^3/h to the fresh water receptor. Assuming, that outflow equals inflow to the well, calculations based on drawdown assessed in reference to the inferred position of the water level at +0.25 m (reported in the drilling report) were also run against the resultant water level position in the completed well. This estimate also yields the same overall recharge that amounts to 14–15 m^3/h.

The well 5p is a point source of saline pollution. Assuming both constant SO_4 concentration in up-flowing mineral water (about 1000 mg/L) and recharge, the total sulphate load which intruded into fresh aquifers might be approx. up to 1650 Mg and 2600 Mg in years 1980–2000 (the period documented by pumpings) and 1980–2012 (the whole period), respectively. The calculated fluxes are certain for the 1980–2000 period and probable for the period after 2000. The width of saline water plum (and likely the replacement of fresh water) may initially reach approx. 100–120 m according to the Sichardt's formula, but along the down-gradient migration, it possibly grows due to macro-dispersivity.

Over 30-year permanent intrusion has contributed to geogenic deterioration of the chemical condition of shallower fresh water horizons, and consequently to the Sokołowiec Stream and Ścinawka River, and subsequently to the ecosystems dependent on groundwater and surface water ecological conditions.

Quantification of the far-field effects of abandonment of the well 5p requires further research.

CONCLUSIONS

Abandonment of the well 5p in an unprepared way, i.e. unplugged and unsealed manner, was an environmentally inappropriate action, as the well intersects a multi-body system containing fresh and saline groundwaters. In such circumstances, this well has generated a series of adverse effects and risks to the environment: 1) salinization of fresh water-bearing body, 2) generation of mutant and toxic pollutants (BTEX, PAHs and aliphatic hydrocarbons). All of

them originate from hydrogeological and geochemical settings. The research results stipulate to group the conclusions into specific and general ones.

The specific conclusions are as follows: (A) the well should ultimately be closed down because it exerts the very strong salinization impact on fresh water bodies: approx. up to 9 m^3/h, which yielded at least 1650 tons of SO_4 during the period investigated by pumpings (1980–2000); (B) there are yet unknown consequences to potential curative usage of mineral water from the well 5p due to the volume and time of intrusion into the mineralised water-bearing profile; (C) it is presumed, that ongoing bio-geochemical processes in the well are still in a transient phase, therefore, there is no reason to assume that the registered values reflect the terminal level of the risk to the environment; (D) the current geochemical evidences indicate that hydrocarbons found in water from the well 5p are of geogenic origin; (E) functioning of the well as a monitoring point suggests that there was no defined procedure in selecting groundwater monitoring points or the decision on such selection overruled the good practice.

General conclusions deal with the same aspects but in a view of the scale of such phenomena : (A) do privileged pathways made by the "orphans" are able to generate large risks, especially in case of complex hydrogeological settings and/or in the areas of geological CO_2 storage or shale gas exploitation; (B) the presence of "orphans" should be under institutional monitoring and safety assessments; (C) amended regulations should explicitly and definitely solve the case of "orphans"; (D) there should be available a clear set (list) of properties, describing the well representativity to enable making a proper decision on selecting and keeping an observation point in the nationwide monitoring network.

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STRESZCZENIE

Obiektem badań jest otwór studzienny nr 5p (MONBADA nr 1183; UE_ID: PL06G110_004; JCWPd nr 110) zlokalizowany w Sokołowsku (Sudety), pierwotnie planowany jako element ujęcia zaopatrującego w wodę Wałbrzych. Od wykonania (1980 r.), otwór nie był nigdy wykorzystywany z uwagi na złą jakość wody, a w konsekwencji został porzucony. Badania „osieroconego" otworu pokazały skutki trwającego 32 lata porzucenia, które to stworzyło nieplanowany długoterminowy eksperyment i „naturalne laboratorium" w studni. Antropopresja zmieniła naturalne warunki hydrauliczne, powodując efekty uboczne: m.in. zasolenie wód zwykłych, a następnie uruchomienie ze skał toksycznych zanieczyszczeń (BTEX, WWA, węglowodory alifatyczne). Wyniki badań wskazują na potrzebę stworzenia procedury oceny reprezentatywności punktów obserwacyjnych w sieci krajowego monitoringu wód podziemnych i programu weryfikacji istniejących punktów.