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Shale gas impacts on groundwater resources: Understanding the behavior of a shallow aquifer around a fracking site in Poland

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Abstract

Exploitation of shale gas by hydraulic fracturing (fracking) is highly controversial and concerns have been raised regarding induced risks from this technique. As part of the EU-funded SHEER Project, a shallow aquifer used for drinking water, overlying a zone of active shale-gas fracking, has been monitored for more than a year. Early results reveal the functioning of the shallow aquifer and hydrochemistry, focusing on the identification of potential impacts from the shale gas operation. This stage is an essential precursor to modeling impact scenarios of contamination and to predict changes in the aquifer.

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Keywords: shale gas; environmental impacts; monitoring; Quaternary aquifer

1. Introduction

Exploitation of shale gas by hydraulic fracturing (‘fracking’) gained its controversial status after many well owners in the USA, whose wells were in the vicinity of shale gas pads, complained about changes in the quality of their drinking water. For example, studies by Jackson et al. [1] and Darrah et al. [2] suggest that some wells have been contaminated by stray gases, likely due to poor well construction. This followed exemption of shale gas

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developments from much of the pre-existing environmental regulation in the USA [3]. Reports of such problems in the USA triggered public opposition in Europe at the time the first drilling permits were being awarded. As a consequence, a cautious approach is taken in Europe compared to the USA. Several potential impact types have been identified [3] and the need for baseline monitoring prior to any shale gas activity (which is missing in US regulation) has been widely acknowledged by the scientific community [4]. In Europe, Poland is the leader in shale gas exploration and exploitation, as one of the European countries with the largest estimated reserves, and twenty-seven horizontal wells have been hydraulically stimulated since 2010 [5]. Exploration for shale gas resources is generally well perceived in Poland and shows a strong acceptance by the population.

As part of the European approach, the SHEER (SHale gas Exploration and Exploitation induced Risks) Project is one of a small number of research projects investigating shale gas risks, funded by the EU Horizon 2020 program. It aims to develop best practice in order to understand, prevent and mitigate the potential short- and long-term environmental impacts and risks from shale gas exploration and exploitation. Within the SHEER project, three major potential risk areas have been identified: induced seismicity, groundwater contamination and air pollution.

Here, the focus is on understanding the groundwater contamination risks. Although much controversy has centered on the hypothesis that fracking (which is invariably at great depth) might create direct contaminant pathways with upward-oriented hydraulic gradients, previous studies have demonstrated that this is extremely unlikely [6]. Far more likely is pollution from surface or near-surface operations, involving transmission of gas or handling of co-produced waters. To interrogate these issues, a study has been carried out into a Quaternary aquifer, which provides drinking water in the study area and on which a drilling pad of recently-drilled and fracked shale gas wells is located. This shallow aquifer has already been monitored for more than one year, and information regarding the functioning of this aquifer can be extracted from the monitoring data. Thoughts regarding the monitoring of impacts of shale gas exploration on groundwater resources are also included in the discussion.

2. Description of the study area

The drilling pad is located in the Stara Kiszewa concession, about 40 km from the city of Gdańsk, in the Pomerania region, Northern Poland (Fig. 1). The region forms part of the Baltic Basin and has a simple geological structure which is relatively tectonically undeformed.

2.1. Geological and hydrogeological setting of the drilling site

Prior to commencement of any shale gas drilling operations, the drilling pad was constructed with impermeable liners and bunded drainage capture with the purpose of preventing any leakage of fluids at surface (from drilling, fracking or flowback of deep well fluids). The drilling pad hosts three boreholes drilled to a depth of about 4 km (Fig. 2). The vertical borehole (Wysin-1) was drilled in 2013 to prove the stratigraphic sequence. Subsequently two deviated boreholes (with 1 km laterals at depth) were drilled in autumn 2015 (Wysin-2H and Wysin-3H trending ESE and WNW respectively). The horizontal laterals of these boreholes are aligned roughly parallel to the general fault trend in the region (NW-SE faults; [7]) although faulting in the Lower Palaeozoic strata is rather limited [8,9].

The vertical borehole Wysin-1 reaches Middle Cambrian deposits (54.5 m thick; [10]), which consist of black mudstones and clays interbedded with fine-grained quartz sandstones. The horizontal borehole Wysin-3H is drilled into Ordovician marls, claystones and shales belonging to the Prabuty Formation. This layer is relatively thin (~30 m thick). The other horizontal borehole (Wysin-2H) is drilled into Silurian shales, in the lower part of the succession (Wenlock Formation), which are almost 2 km in thickness. The Silurian shales are covered by about 400 m of Permian rocks, which include the Zechstein Formation. The Zechstein, consisting primarily of anhydrite and halite deposits, is effectively impermeable and acts as a sealing layer - as it does for many North Sea oil and gas reservoirs. It is followed by 600 m of Triassic strata, including Buntsandstein claystone-mudstones and Muschelkalk marls and dolomites with limestone intercalations and claystones. These are overlain by 300 m of Jurassic deposits. Cretaceous sediments (600 m thick) lie discordantly on the Jurassic: Lower Cretaceous sands and mudstones and Upper Cretaceous glauconitic sandstones, marly limestones and marls [7]. Finally, the sequence is completed by 100 m of Tertiary sediments from the Miocene (carbonaceous silty clays interbedded with sandy silts) and 100-150 m of Quaternary sediments resulting principally from the last glaciations.

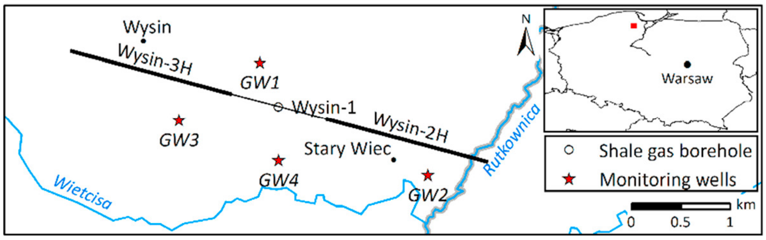

Fig. 1. Location of the drilling pad (marked Wysin-1), the surface projections of the laterals in theWysin-2H and Wysin-3H wells, the groundwater monitoring wells (GW1-4) that forms the core of the aquifer monitoring network. Red square in insert map marks the location of the study area.

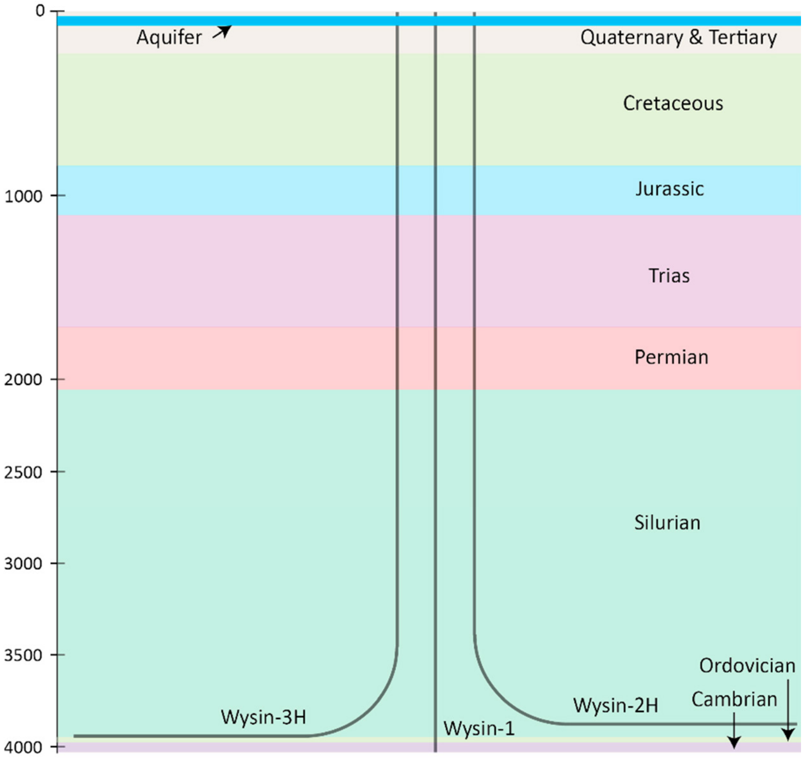

Fig. 2. Location of the shale gas boreholes and the stratigraphy through which they are drilled.

The Quaternary sediments form a multi-layered aquifer, the most productive horizon of which hosts the Intra-moraine reservoir Gołębiewo (Main Groundwater Reservoir No. 116). The region is rural and the population around the shale gas pad relies on this aquifer as a source of drinking water and for agricultural use. South and east of the pad run the rivers Wietcisa and Rutkownica (a tributary of the Wietcisa), which act as local discharge zones for the aquifer. The general direction of the groundwater flow is from north to south towards the Wietcisa River [7].

2.2. Stratigraphy of the Quaternary aquifer

The Quaternary aquifer consists of a succession of permeable strata (sands and gravels) alternating with less permeable sediments (silt, till and clay). Originating from the last glaciations in Poland, the stratigraphy is likely to be strongly heterogeneous with intersecting lenses of differing sedimentary materials [11,12].

Fig. 2 shows a simplified stratigraphy based on the groundwater borehole logs. The presence of a more or less continuous low-permeability layer gives the aquifer a semi-confined to confined character.

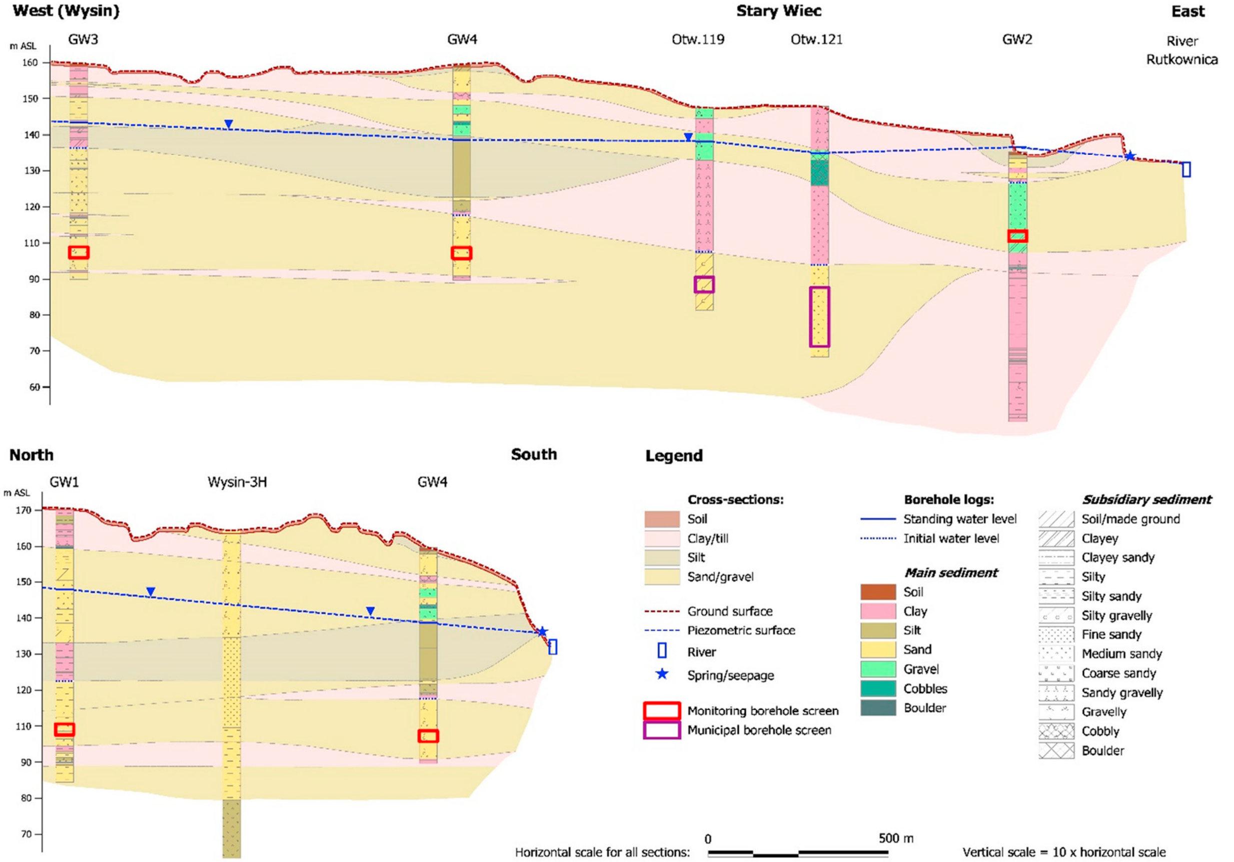

Fig. 3. Simplified 2D-vertical geological cross-sections (location identified in Fig. 1) based on the stratigraphy recorded during the drilling of the monitoring wells and from nearby wells. For clarity, the diameter of the wells has been exaggerated, all monitoring boreholes are 150 mm diameter.

2.3. Groundwater monitoring network

A groundwater monitoring network was installed during autumn 2015 and consists of four groundwater wells; their locations are shown in Fig. 1. The wells were drilled into the main Quaternary aquifer. The layout was designed bearing in mind the anticipated dominant groundwater flow direction imposed by the hydraulic effects of the gaining streams that partially penetrate the aquifer. Thus GW1 is located upgradient of the shale gas drilling pad and acts as a control, GW2 and GW3 are downgradient of Wysin-2H and Wysin-3H respectively, and GW4 is downgradient from the drilling pad (Fig. 1). It is worth noting that GW2 is a flowing artesian well which is kept closed with a pressure cap except during sampling.

The groundwater monitoring started as soon as the monitoring wells were installed. The baseline monitoring lasted for 6 months, until the stimulation of the horizontal wells in June and July 2016 (Wysin-2H and Wysin-3H respectively). During this 6-month period, four sampling rounds were carried out (in December 2015, February, March and April 2016). One site visit was completed in June 2016, between the two fracking periods. A sample of 'frac' fluid was collected during the fracking at Wysin-2H, as well as a sample of flowback fluid 24 days after completion of the fracture stimulation at Wysin-2H. Post-frac monitoring has been ongoing since August 2016, with one visit per month in 2016 and an average of one visit every two months in 2017.

3. Material and methods

3.1. Meteorological data

A meteorological station (Davis Vantage Pro2 Plus) was installed in February 2016 in the village of Stary Wiec (Fig. 1), as part of the equipment for monitoring air pollution within the SHEER Project. The station measures temperature, atmospheric pressure, rainfall, wind speed and direction, solar and UV radiation with a time step of one minute. The reference evapotranspiration (ET_0) is automatically calculated by the station using the measured parameters. The data are consequently aggregated to give a more convenient time step (daily).

3.2. Monitoring of groundwater levels

A downhole probe (CTD-Diver, Schlumberger) was installed in each borehole at the mid-point of the screen, in December 2015 (see screen locations in Fig. 3). These probes measure the pressure above the transducer, the groundwater temperature and specific conductivity at 15-minute intervals. Their specifications vary from one well to another. Three transducers (GW1, GW3 and GW4) have a 100-m range and measure the pressure with an accuracy of ±5 cm and a resolution of 2 cm. The transducer in GW2 has a range of 50 m with accuracy of ±2.5 cm and resolution of 1 cm. Since the transducers are non-vented (measuring absolute pressure), a barometric transducer (Baro-Diver, Schlumberger) was installed in GW1 to record the variations of atmospheric pressure and air temperature. This transducer has a range of 1.5 m, with accuracy of ±0.5 cm and resolution of 0.2 cm. Transducers in the non-flowing wells have direct-read cables that can be connected directly to a computer at surface, with no requirement to remove the transducer during data download. The transducer in GW2 and the barometric transducer are suspended on high-quality cord (Dyneema) and have to be removed to download the data. The data are downloaded during each site visit from each transducer. When the transducers' memory is nearly full, they are restarted to avoid gaps in the data.

Groundwater pressure data have been processed to remove abnormal data if present. Data are regularly checked against manual measurements of groundwater levels to identify any discrepancies. Data are compensated for barometric effects using the graphical method from Gonthier [13] for GW2 (closed well) and using the regression deconvolution described in Rasmussen and Crawford [14] and implemented in BETCO by Toll and Rasmussen [15] for GW1, GW3 and GW4 (open wells).

3.3. Purging and sampling of the wells

The wells are purged using a submersible pump (GRUNDFOS® model SQE-2-85) placed a few meters below the water level (approximately 2 m below the previously observed drawdown to avoid the pump running dry) to ensure a good-quality purge. Samples are taken after removal of three wellbore volumes and following stabilization of the physico-chemical parameters. The physico-chemical parameters (temperature, pH, electrical conductivity, specific conductivity, dissolved oxygen, and oxidation-reduction potential) are measured using a multi-parameter probe (model YSI Professional Plus); this is calibrated each day and measurements are taken whilst the probe is submerged in a bucket.

For major ion and metal analyses, a 1-litre plastic bottle is filled up to the neck. In addition to the laboratory measurement, total alkalinity is determined in the field using a HACH® kit for field titration. Each titration is performed with 0.16 N sulfuric acid on 100 ml of freshly collected sample to which a Bromcresol Green-Methyl Red indicator powder pillow has been added. Major ions, metals and dissolved gases are analyzed by the Concept Life Sciences Laboratory (East Kilbride, UK).

Samples for water stable isotope analysis ($\delta^{18}O$ and $\delta^{2}H$) are collected in 15-ml glass vials. To avoid the presence of bubbles, the vial is submerged in the bucket and the cap screwed on while water is flowing through the bucket. Each sample is taken in sequential triplicates. The vial cap is taped to minimize water losses (and thus fractionation) by evaporation. These samples are analyzed at the Scottish Universities Environmental Research Laboratories (SUERC, East Kilbride, UK).

All bottles are free of preservatives and are rinsed before sampling. Samples are kept at 4°C during transport and storage before being dispatched to the laboratories.

3.4. Analytical methods

Filtration and acidification prior to analysis are performed by the laboratory for cation and metal analyses. They are analyzed either by Inductively Coupled Plasma - Optical Emission Spectrophotometry (ICP-OES) or Inductively Coupled Plasma - Mass Spectrometry (ICP-MS) depending on the element.

Anions are analyzed by Discrete Analyzer for SO_4^{2-} and Ion Chromatography (IC) for Cl^-, F^- and Br^-. In addition to being determined in the field, alkalinity is measured in the lab by titration on filtered samples (since December 2016, analysis has been undertaken by Discrete Analyzer).

Stable isotopes $\delta^{18}O$ and δ^2H are analyzed on a Thermo Scientific Delta V mass spectrometer and VG Optima mass spectrometer respectively. Final values for $\delta^{18}O$ and δ^2H are reported as per mil (‰) variations from the V-SMOW standard in standard delta notation.

3.5. Recharge model

A recharge model was built in order to explain the observed groundwater level variations and the water stable isotope signature in the groundwater. The recharge model is based on the method developed by the United Nations Food and Agriculture Organization (FAO) [16]. Although this model was originally developed for irrigation purposes at field scale, it has successfully been used at catchment scale [17]. Data from the meteorological station in Stary Wiec are used as input. Other variables are estimated using tables available in Allen et al. [16]. A runoff coefficient of 0.2 was estimated based on the soil type and cover [18]. Five types of vegetation and crops representative of the soil occupation at the catchment scale were considered: wood, wheat, corn, rye grass and pasture. A sub-model was developed for each vegetation type. The final model represents an averaged recharge model at the catchment scale, with each sub-model weighted by the aerial surface covered by the corresponding crop (25% Wheat, 25% Rye Grass, 20% Wood, 15% Corn and 15% Pasture). This distribution is based on field observations.

4. Results and discussion

4.1. General trends in groundwater level variations

The variation in groundwater levels in the four monitoring wells are shown in Fig. 4. Excluding variations resulting from pumping during sampling visits, four significant periods can be defined based on the water level variations in GW3. Groundwater levels were relatively stable (±0.05 m) during the first month of monitoring in all the wells. Groundwater levels then significantly increased in GW3 at the end of winter 2015-16, continuing into spring 2016 (+1.4 m). During this period, groundwater levels increased slightly in GW1 (+0.12 m) and GW4 (+0.05 m) whereas they decreased (albeit with short-term fluctuations) in GW2 (-0.2 m). During summer and early autumn 2016, the levels were stable in GW3 and GW2 and slightly decreasing in GW1 (~ -0.1 m) and GW4 (-0.05 m). Finally, a general increase is observed since autumn 2016 (at least until April 2017). This increase does not happen at the same time and with the same amplitude in all the monitoring wells: it is first apparent in GW2 in October 2016 (increase of ~30 cm in 6 months), followed by GW4 in November 2016 (~30 cm in 4.5 months) and finally GW1 and GW3 around the same time (beginning of 2017; ~30 cm in GW1 and ~40 cm in GW3 over 3 months). Considering these four periods, the same general trend is observed in the four wells with varying amplitude and time lags. These observations suggest little recharge reached the aquifer from May to October in 2016.

These observations do not tie in with the general rainfall pattern, characterized in 2016 by a dry spring, a very wet summer and quite a wet autumn. Winter 2016-17 was also rather dry. Assuming a constant recharge rate (e.g. 30% of rainfall), this would suggest that the current groundwater level increases result from recharge occurring in the summer period and reaching the wells with a time lag (variable depending on the location of the wells). Otherwise, the recharge pattern is different from the rainfall pattern.

Finally, some abrupt variations of groundwater levels are observed in GW2 around the period of the fracking. However, some were also observed in this same well before the fracking. These same variations are smoother in GW1 and GW4, and are possibly masked by the general increasing trend in GW3. These variations are not yet fully understood but may be related to the confined nature of the aquifer near the rivers.

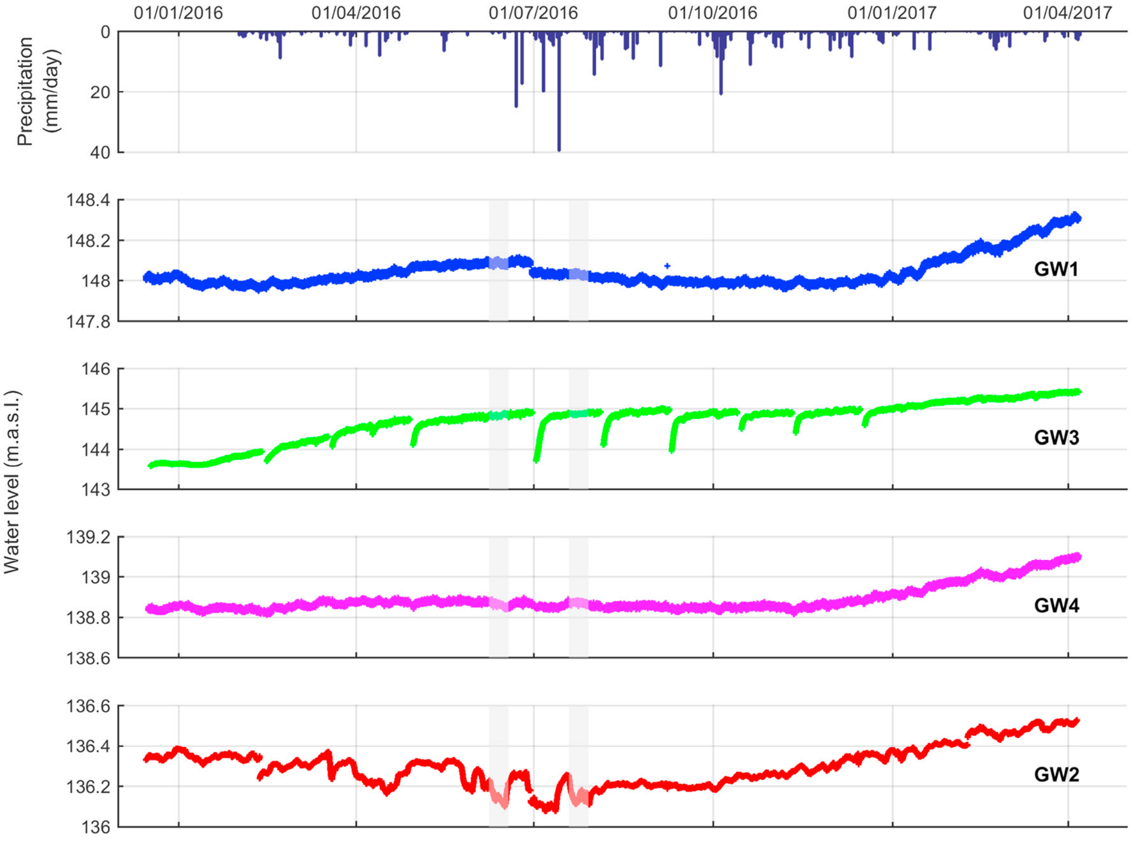

Fig. 4. Daily rainfall and variations of groundwater levels in the monitoring wells during the monitoring period. For GW3, note: (1) the difference of scale for GW3, with ticks every meter, and (2) the distinctive recovery periods (~1 week) as a result of pumping for sampling.

4.2. Water stable isotopes ($\delta^{18}O$ and $\delta^{2}H$)

Samples analyzed for water stable isotopes plot near the interpolated Local Meteoric Water Line (LMWL; [19,20]; Fig. 5). As expected in such settings, this observation confirms that the recharge comes from recently infiltrated precipitation. The samples plot between the average monthly rainfall signatures of April and October and the interpolated annual signature. It suggests that either the recharge is yearly averaged (as often observed in groundwater under a temperate climate) or occurs principally during the months of April and/or October.

Regarding the impact of shale gas on shallow groundwater resources, the isotopic signatures of samples taken before, during and after the fracking are similar, considering the laboratory uncertainties on the measurements. In contrast, the stable isotope signature of the flowback fluid is significantly different. In the event of flowback fluid leakage to the aquifer, a shifting of the groundwater signature towards the flowback fluid would be expected.

4.3. Recharge model

Although precipitation levels were relatively low at the end of winter 2016-17 (47.4 mm), they do contribute to aquifer recharge (25.9 mm, > 50% of the total precipitation). Only a small volume of the spring rainfall and intense rainfall of summer 2016 is indicated to reach the aquifer (17.9 mm, ~7% of the rainfall during spring and summer, with no recharge in May or June 2016). Most of the precipitation is lost by evapotranspiration from the crops. After harvesting during late summer/early autumn, the aquifer recharge from precipitation becomes more efficient (132 mm of recharge, 60% of the precipitation) from October until the next cropping season (Fig. 6).

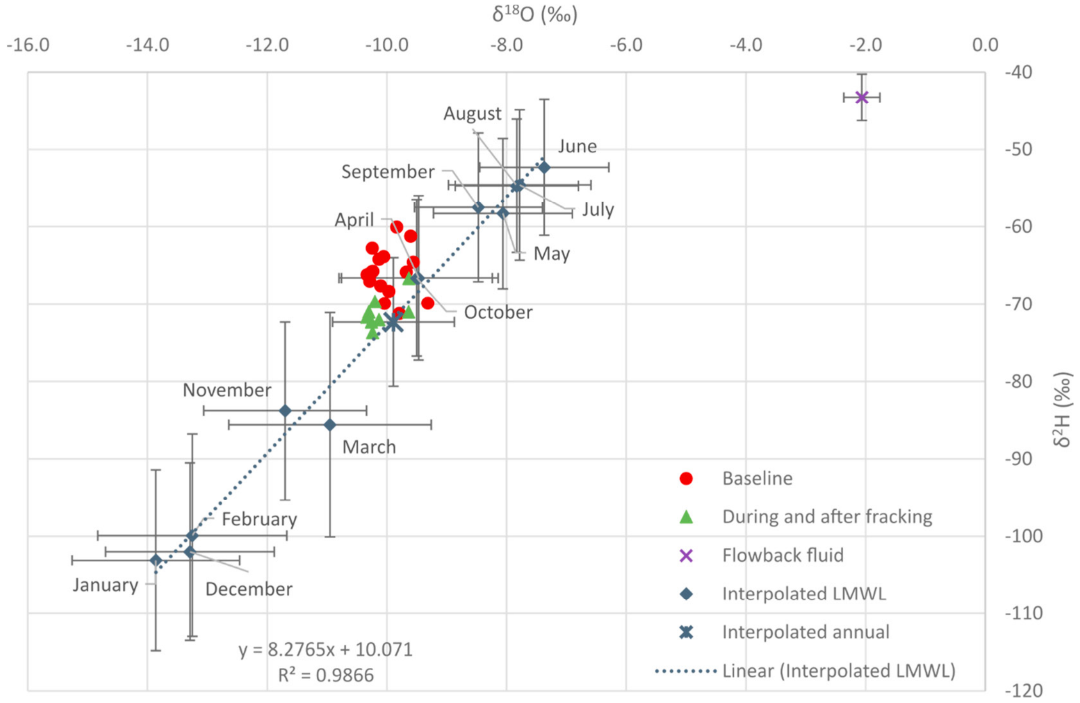

Fig. 5. Stable isotope signature of groundwater. LMWL data from IAEA [20] and interpolated by Terzer et al. [19]. Error bars for red dots and green triangles are the same as for the purple cross. For clarity, these have been omitted.

The recharge model based on 2016 precipitation data indicates that most of the recharge occurs before April and after October. Using just the single year of available data does not allow accurate or definitive examination of any possible linkage between the isotopic composition of the groundwater and the average isotopic signature of the rainwater, nor does it allow unequivocal determination for the occurrence of recharge in April and/or October. All that can be stated here is that, in 2016, the highest recharge rate of 39.9 mm occurred in October.

The recharge pattern observed in 2016 would explain the water level variations observed in the wells i.e. a general increase since October 2016. The lag time between the recharge event and the observed change in groundwater level, as well as the observed difference in the water level increase in the different monitoring wells, reflect the complex structure and heterogeneity of the Quaternary aquifer. The confining till layer, with a low hydraulic conductivity and a variable thickness, can significantly delay the recharge to the aquifer. In some places, this layer is expected to be discontinuous, thus creating local recharge zones. In addition, the actual crop spatial and temporal distribution might also impact on the spatial variability of the recharge to a lesser extent.

Fig. 6. Recharge model calculated using the FAO method [16] using a variety of types of groundcover vegetation and crops (25% Wheat, 25% Rye Grass, 20% Wood, 15% Corn and 15% Pasture).

4.4. Groundwater chemistry and other parameters

Analytical results (not shown here) indicate that the groundwater quality is similar in the four monitoring wells. The groundwater has a low mineral content, with specific electrical conductivity values varying between 400 and 500 µS/cm. Calcium and bicarbonate are the dominant ions ($Ca-HCO_3$ water type), as would be expected in an aquifer located in highly transmissive Quaternary sediments that are regularly recharged by recently infiltrated rainwater. The groundwater temperature of the aquifer is about 8°C and stable all year round. The groundwater has a good chemical quality and is suitable for use as drinking water for all parameters measured except manganese, where the concentrations are two to three times the maximum permitted concentration for drinking water [21]. Groundwater samples have not been tested for microbial quality. The chemical quality of the groundwater is similar to reported groundwater quality in other aquifers in the region [12].

In contrast, the frac fluid and flowback fluid show very distinct chemical signatures, differing markedly both from each other and from the shallow groundwater. As a result of mixing between chemicals (e.g. choline chloride) and surface water, the frac fluid has sodium and chloride concentrations approximately 20 times higher than those in the groundwater, 4-5 times lower calcium levels, twice as much magnesium and 10 times as much manganese. The flowback fluid is highly mineralized, with concentrations of major and minor ions several orders of magnitude higher than concentrations in the groundwater. The flowback fluid has a similar chemical composition to brines from the Canadian Shield [22]. Should any leakage of flowback fluid to the aquifer occur, an obvious change in the groundwater chemistry would be expected, given the very different chemical composition of the flowback fluid (in a similar manner to the changes anticipated in water isotopic composition in the event of a leak). To date, the groundwater chemistry has been relatively stable and no short-term or early-stage impacts have been identified.

5. Conclusion and perspectives

A robust understanding of the composition and behavior of hydrogeological systems near a shale gas site is essential in this controversial debate. The shallow aquifer surrounding the shale gas study site in Poland is used by the local population for drinking water and irrigation. It is a typical Quaternary aquifer with a heterogeneous structure consisting of permeable layers of sands and gravels alternating with less permeable layers, resulting from the last glaciations. The aquifer has a semi-confined to confined character around the drilling site. During the monitoring period, the wells show similar variation in water levels, although with variable time lags and intensity, a result of the aquifer heterogeneity which dampens and delays the signal. These water level variations can be explained by a simplified recharge model, which shows that, in 2016, most of the recharge occurred during the months of October to December. The groundwater chemistry is typical of young, shallow aquifers with regular recharge and low residence times, resulting in relatively low mineralization. This is demonstrated by the specific conductivity (400-500 µS/cm), major ion chemistry ($Ca-HCO_3$ water type) and water stable isotope composition (plots on LMWL). All these parameters remained stable during the baseline monitoring period.

The flowback fluid produced from shale gas operations has a significantly different chemical composition and isotopic signature from the natural groundwater. As a result, some change to the chemical and isotopic composition of the groundwater would be expected in the event of flowback fluid leakage to the aquifer. This preliminary interpretation suggests that there have been no short-term impacts on the physico-chemical properties of the groundwater during the monitoring period to date (less than one year). Similarly, no changes to water levels were detected that could be attributable to hydraulic fracturing. Statistical methods are currently being tested to allow drawing of robust conclusions concerning the impacts or absence of impacts on groundwater resources, and their statistical significance. In addition, the flowback fluid composition has not been fully characterized and additional analyses are planned to improve this understanding.

The recharge model will be used as an input to the hydrogeological model that is being developed to provide further understanding of the aquifer behavior. This will also help to validate the recharge model through numerical modeling of the observed water levels and give some insights on the influence of aquifer heterogeneity on the aquifer reaction to recharge. Once the model has been calibrated, it will be used to assess the impacts of various contamination scenarios on the aquifer and its groundwater resource.

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