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Polish Geological Survey

Polish Hydrogeological Survey

Environmental Aspects of Hydraulic Fracturing Treatment Performed on the Łebień LE-2H Well

FINAL REPORT

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1 Introduction

1.1 Major aim of this study

The major aim of works of a consortium led by the Polish Geological Institute – National Research Institute (PGI-NRI) was to assess environmental impact of hydraulic fracturing carried out in August 2011 in the Łebień LE-2H exploratory well operated by the Lane Energy Poland company of the 3Legs Resources Group. The works were ordered by the Ministry of Environment in agreement with the operator. In that well, the hydraulic fracturing of a horizontal section has been performed for the first time in Poland. The permission to drill that well was granted in the license no. 16/2007p for prospecting and exploration of unconventional gas resources. The hydraulic fracturing operations were conducted in accordance with Annex no.1 to the Work Plan approved by the Director of the Regional Mining Authority in Poznań. In accordance with the above mentioned permit. The Łebień LE-2H well has targeted unconventional gas resources in fine-grained rocks of the Silurian and Ordovician.

1.2 Venture characteristics

The Lane Energy Poland Ltd.. of the 3Legs Resources group is conducting exploration at Rekowo Lęborskie locality in line with the conditions of the concession No 16/2007p issued on 23.10.2007. The concession has been granted for prospecting and exploration of oil and gas resources in the Lębork license area situated in onshore part of the Baltic Sea basin in northern Poland. The works were aimed at exploration of occurrences of gas in Lower Silurian and Ordovician shales and assessment of technical possibilities for establishing its commercial production.

The Łebień LE-2H well was localized at the plot no.147/1, Rekowo geodesic precint, Nowa Wieś Lęborska commune (Lębork District, Pomeranian Voivodeship). The drilling rig occupies an area of 3.74 hectares, situated by the local (district) road from Łebień to Rekowo Lęborskie, in north-eastern part of the commune. The well site is 2 to 4 km distant from areas of the neighboring communes of the Lębork (Wicko) and Wejherowo districts (Choczewo and Łęczyce).

Within the frame of exploratory works, a vertical well named LE-1 was made down to 3.5 km depth in the license area in 2010 (drilling started in June 2010) and hydraulic fracturing treatment was performed on a small scale (single stage hydraulic fracturing treatment) in November 2010. Drilling of the second well with a horizontal section, named LE-2H, was completed in June 2011. Total depth of the well is 4,075 m and the horizontal section is oriented towards the south—southwest (SSW) and 1,000 m long.

The drilling rig had its own water intake to cover needs for cooling and hydro-fracturing operations. The water intake is situated in western part of the well site area. The water supply system consists of two wells: a production well (no. SW-1) and a backup one (no. SW-2), drawing water from Quaternary aquifer. The exploitable water resources approved for that intake are equal Q_e=10,0 m^3/h (in accordance with Decision No. 370/10 of the Head of the Lębork District, ref. OŚ.III.6224-01/01, from June 24, 2010 –

water rights permit /water supply consent/ for construction of casings of the SW-1 and SW-2 wells and installing pumping system at the site of the Łebień LW1 well).

In the well site area, two reservoirs for storing technical water were built by excavation in the ground. Storage volume of these reservoirs is 6,000 i 12,000 m^3.

2 Characteristics of the studied area

2.1 Geomorphology, topographic features and hydrography

According to physicogeographic subdivision of Poland [Kondracki, 2000], the studied area belongs to the Pobrzeże Koszalińskie (Koszalin Coastland) macroregion and the Wysoczyzna Żarnowiecka (Żarnowiec Plateau) mesoregion, which border the Łeba and Reda proglacial river valley to the south and west, the Słowińskie Coastland to the north and the Kaszuby Coastland (Gdańsk Coastland macroregion) to the east.

The Wysoczyzna Żarnowiecka (Lęborska) Plateau is a ground moraine left by the youngest glaciation and cut by post-glacial channels and valleys into plateau hillocks. The well site is situated at the Tawęcińska Kępa Hillock, the top surface of which rises up to 90 m asl in its northern part and up to 70 m in the southern. To the east, the Tawęcińska Kępa Hillock is separated from the Salińska Kępa Hillock by the Zwartowska channel and Kisewska Struga valley and to the west - from the Redkowicka Kępa by the Reknica (Lędziechowska) valley. Valley depressions with flat floors (Fig. 1) are used by rivers and streams: Kisewska Struga (tributary of Łeba river) and Chełst (flowing into Sarbsko lake) and Reknica (Rekowska Struga, tributary of Kisewa river) and Lędziechowska Struga (tributary of Białogardzka Struga river).

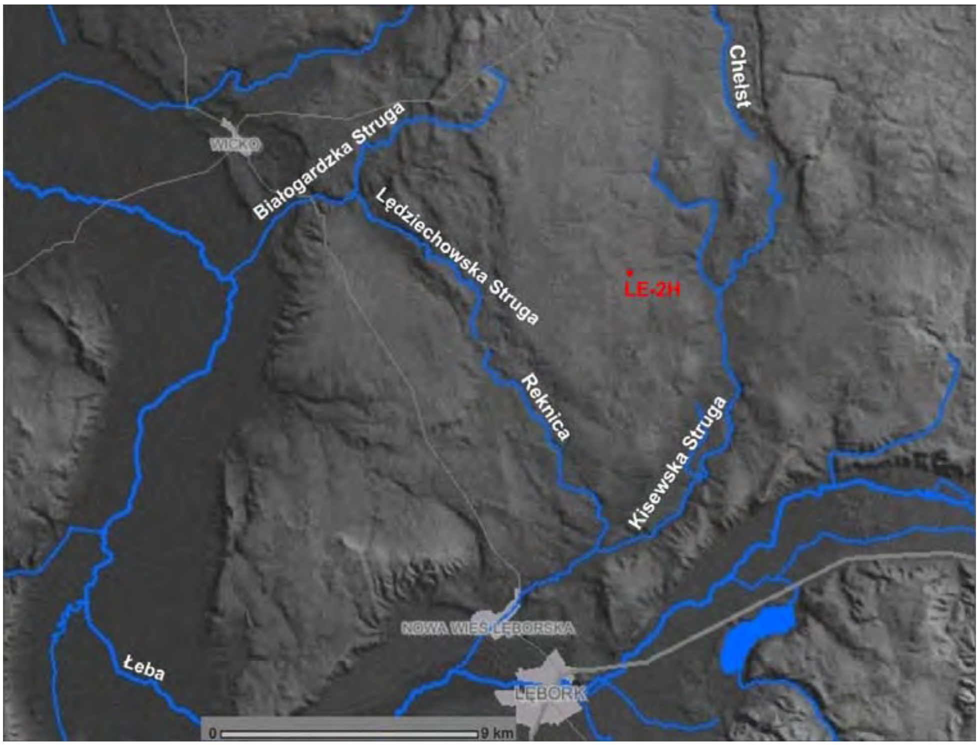

Fig. 1. Topography of land surface and River network (source: CBDG)

The depressions are important for the wealth of nature in the studied area as they are the sites of occurrence of forest, meadow and peatbog communities and numerous hydrographic elements. The depressions play the role of local ecological corridors (Studium…, 2010).

The studied area is situated within the boundaries of drainage basin of the Łeba River, one of rivers of the coastland. The creek flowing at the smallest (2.5 km) distance from the well site is the Kisewska Struga, a right tributary joining the Łeba River under the name of Kisewa (Fig.2) The water divide separating drainage basins of the Kisewska Struga in the east and that of the Białogard channel in the west passes through area near Tawęcino village, elevated 95 m asl. Western part of the Tawęcińska Kępa is drained by the Reknica and Lędziechowska Struga creeks which join the Kisielewska Struga and Białogardzka Struga, respectively. The creeks are characterized by development of multiple narrow channels, especially close to their springs.

Fig. 2. Kisewska Struga Creek (June 2011)

Drainage ditches and depressions without natural water outflow are fairly common in the vicinity of the well site. A shallow waterlogged depression with peat bogs, occurring in area of Rekowo Lęborskie, 1.3 km to south-east of the well site, was filled with water in July 2011.

2.2 Geological structure

The studied area is situated in western part of the East European Craton, in central part of the Łeba Elevation which represent western part of Peribaltic Syneclise. The crystalline basement, built here of gneisses (Morawski W., 1990 r.), occurs at depths of over 3,000 m. The basement is overlain by thick sedimentary cover of Cambrian, Ordovician, Silurian and Permian rocks. With a stratigraphic gap comprising the Devonian, Carboniferous and Lower Permian, up to the Zechstein. The latter stage is represented by claystones, siltstones and sandstones in lower parts and mainly limestones, dolomites, gypsum and rock salt in the upper. Silurian rocks – claystones – are characterized by very large (about 2,000 m) thickness. The Silurian and Ordovician shales are the primary targets for prospecting for potential unconventional gas resources.

Mesozoic rocks are represented by successions of Triassic claystones and calcareous siltstones, Jurassic sands, sandstones and claystones and Cretaceous sandstones, claystones and siltstones about 500 m in thickness.

The Mesozoic rocks are overlain by Paleogene sediments 70 to 200 m in thickness. After retreat of the sea, terrestial conditions predominated till the Middle Eocene when a new transgression took place. The Miocene is represented by terrestial sediments accumulated in freshwater lakes reservoirs (Morawski, 1990).

The section of Quaternary sediments is reduced in result of successive stages of glacial exaration processes and erosion by meltwaters. In the well site area, a layer of sandy till of the Pleistocene, 3 to 4 m in thickness, occurs beneath the land surface. That layer is underlain by clastic sediments of the Last Glaciation: various grained sands with admixture of gravels and single pebbles. Clayey and dark grey coally silts, found at the depth of 44 m below the land surface, were assigned to the Neogene (Wolski, 2010).

2.3 Hydrogeological conditions

The drilling pad area and its direct vicinity belong to the Coastland subregion in the hydrogeological regionalization of fresh groundwaters of Poland (Paczyński, 1995; Paczyński, Sadurski Eds., 2007).

The Quaternary aquifer occurring beneath the tills is here the major usable water-bearing horizon (GUPW in the PGI-NRI classification) and the primary source of water supply for household (domestic), commercial, and other purposes. This horizon is built of sands varying in granulation and gravels of the Mid- and North-Polish Glaciation, from 5 to 40 m in thickness and isolated from the surface by tills 3 to 20 m in thickness. The confined or locally unconfined water table stabilizes at the level from 30 to 100 m asl. In the well site area, the water table is confined and occurs at the level of 60.24 m asl (Wolski, 2010). In the studied area the usable water-bearing horizon occurs in depth interwal from 10 to 20 m below land surface. In the water intake situated in the well site area the groundwater table has been recorded at the depth of 14.4 m below the land surface in July 2011.

The water of this aquifer is drawn by many wells with potential output rate ranging from 10 to 120 m^3/h. The hydrogeological conditions are found to be the least advantageous in marginal zone of the Łeba proglacial stream valley (Prussak, 1998). Because of erosional dissection of the land surface (Kisewska Struga valley) and presence of sandy intercalations in tills, the usable Quaternary aquifer is characterized by relatively high coefficient of renewable resources – 540 m^3/24h km^2, and disposable resources corresponding to that value – 280 m^3/24h km^2 (Prussak, 1998).

The course of hydroisohypses in the studied area shows predominating influence of the Łeba River and its tributaries on regional drainage base. It may be noted that the hydraulic gradient is small and transmissivity high with low specific flow rate (Prussak, 1998). The regional direction of water flow is to the south and south-east (Annex 2).

As shown by an original analysis of the GIS MhP database „Łęczyce Sheet of Hydrogeological Map of Poland at the scale 1:50 000 *First Aquifer – Occurrence and Hydrodynamics* (Kwaterkiewicz, Nerkowski, 2006), the above mentioned Quaternary aquifer is at the same time the first aquifer from the ground surface. However, sandy intercalations are fairly numerous in the till which seals that aquifer. This gives rise to origin of local occurrences of shallow -seated water-bearing horizons with variable and discontinuous water table, varying in geological conditions and properties of water-bearing sediments. These shallow water-bearing horizons are exploited through hand dug wells in the studied area. In turn, all the water intakes supplying public drinking water systems are drawing water from the Quaternary aquifer which is confined by the above mentioned tills.

The assessment of the degree of vulnerability of the major usable water-bearing horizon to pollution at the middle level (Prussak, 1998) has been confirmed in the course of compilation of information layers *„First Aquifer – Vulnerability to Pollution and Water Quality"*). The approximated time of exchange of water volume stored in unsaturated zone of the first aquifer (MRT – Mean Residence Time) was estimated at 30 years (compare *Influence on groundwater,* pp. 55-56).

The Łebień drilling pad area is situated beyond the extent of any major groundwater reservoirs. The cosest are „Salino intermoraine reservoir" - the Major Groundwater Reservoir No. 108 and „Proglacial stream valley of the Łeba River" - the Reservoir no. 107, situated to the north-east and south of the site, respectively. Documentation of the two reservoirs has been completed before the year 2010 but decisions establishing their protection zones and enforcing prohibitions and limitations on land use were still not issued by the Director of the Regional Water Management Board.

In the studied area, usable aquifers also occur in sediments of the Neogene and Paleogene. Two Neogene aquifers are related to Miocene fine-grained sand series not exceeding 40 m in thickness. The lower horizon occurs at depths ranging from 0 to 75 m asl, and the upper – at depths from 60 to 100 m asl. These horizons are characterized by fairly limited water resources. They are exploited only in the Łeba proglacial stream valley and its marginal zone (except for the studied area) by drilled wells drawing water from hydraulically connected Miocene and Quaternary aquifers. The Paleogene horizon is related to the Oligocene glauconitic fine-grained sands 10 to 25 m in thickness, which occur at the level of 40-80 m asl (Paczyński, Sadurski, Eds., 2007).

The studied area is situated within the area of the groundwater body (JCWPd in

Polish) no. 11, comprising drainage basins of the Słupia, Łupawa and Łeba rivers. The drainage basins were found to be characterized by good quality and relatively large resources of groundwater (Paczyński, Sadurski, Eds., 2007).

In the Łeba Elevation area, mineral water of the Cl-Na type may occur at relatively shallow depths. According to the *„Map of Management of Groundwater Classified as Mineral Raw Materials in Poland"* at the scale 1:800 000 (Felter and others, 2011), the mineral water may appear already at depths of 300 m below ground surface. Water occurring in the Cretaceous and Jurassic is characterized by mineralization up to 10 g/dm^3 and temperature below 20°C. In Triassic aquifers the mineralization rises to about 25 g/dm^3, the recorded temperatures exceed 20°C and waters is often enriched in iodine as stated in the Lębork IG-1 well, the closest to the Łebień well site.

Mineral water occurring in the Permian (Zechstein) mainly includes concentrated brines with mineralization up to or even over 250 g/dm^3. The brines are separated from deeper-seated aquifers by a 3,000 m succession of impervious rocks of the Silurian (2,000 m of claystones and shales) and Ordovician (1,000 m of marly and clay limestones). Some small inflows of water with mineralization from 180 to 200 g/l and temperature up to about 70°C were found in Cambrian quartzitic sands. Rocks of the crystalline basement appear do not yield water in general (Felter and others, 2011; Paczyński, Płochniewski, 1996).

2.4 Land use patterns and landscape values

Land use patterns and character of housing

Land use patterns in direct neighborhood of the drilling pad area are characterized by predominance of agricultural lands, arable lands, pastures and meadows (Fig. 3). Small forest complexes occur at distance over 1 km to the south-east of the drilling pod and 3-5 km to south-west and east. The villages closest to the well site include Łebień, Karlikowo Lęborskie, Rekowo Lęborskie, Obliwice and Tawęcino.

The well site area is situated in the zone of the agricultural-forest character, predisposed to multi-functional development of villages (Studium…, 2010).

Concentrated housing construction prevails in Łebień, Rekowo Lęborskie and Obliwice villages, whereas housing is scattered in Karlikowo Lęborskie only. Both single and multi-family housing is found in this region. The latter generally predominates in villages such as Łebień and Obliwice where State Agricultural Farms were located in the past. In the remaining villages single family housing prevails.

Fig. 3. The Łebień drill pad viewed from the east; Rekowo Lęborskie, June 2011.

Economic situation

Agriculture dominates the economy in the region and good quality of arable soils creates chances for further development. The major production directions of agricultural individual farm units include cultivation of animals and mixed production. Grains (mainly rye, wheat and barley) predominate in crops of individual farms. The mean area of the individual farms in the Nowa Wieś Lęborska commune is 22,3 ha. Private-owned farms predominate here whereas arable lands of the former State Agricultural Farms were in part taken over by the Agricultural Property Agency of the State Treasury and leased to individual farmers or other entities.

Technical-engineering infrastructure

Individual houses, including those of farmers, are heated mainly with coal-, wood- or coal dust-fired furnaces. Recently oil and liquid gas furnaces began to be popular in home heating. In turn, radiant electric panels or space heaters are still very rarely used. In the case of communal residential buildings, including those built for employees of the State Agricultural Farms, heat is supplied by local boiler plants. A systematic modernization of heat sources and heating systems is planned. It should be added that renewable energy resources, such as wind, solar and hydropower or biogas have not been used for home heating in the Nowa Wieś Lęborska commune up to now.

A first stage gas pressure reducing and metering station with capacity sufficient to cover needs of the whole Nowa Wieś Lęborska commune is located at Mosty. Although high pressure gas pipeline DN 200 passes through the area of the commune, the distribution network is still underdeveloped and only 19.3 per cent of the entire population have access to natural gas. There are plans to build a new transit high pressure pipeline DN 500 (called as the Northern Pipeline) which would be passing through area of the Nowa Wieś Lęborska commune. The concept of development of distribution network include supply of natural gas for industrial consumers. It is also planned to build a medium pressure pipeline network from the pressure reducing station to the Nowa Wieś Lęborska village and from the second stage pressure reducing station SRI located next to the Farm Frites Poland plant to the Pogorzelice village. The plans also include development of the distribution network in the Nowa Wieś Lęborska commune but on a small scale, just in order to comprise Nowa Wieś Lęborska, Lubowidz, Leśnice and Pogorzelice villages.

Rural residential community water systems are pumping water from wells for supplying the village waterworks. Some waterworks act as collective water supply systems for a few villages as this is in the case of Darżewo - Laska, Kębłowo Nowowiejskie - Łowcze, Krępa Kaszubska - Darżkowo, Tawęcino - Karlikowo Lęborskie.

All the water intakes have direct protection zones, which were established in accordance with requirements given in water rights permits. The waterworks network covers 99% of the commune. The water intakes from Łebień, Obliwice and Tawęcino are the closest to the Łebień drilling pad area.

Waste water management is underdeveloped. The waste water treatment plant at Łebień, capable to treat 179.4 m3 load of sewage per day, is reported to be in poor shape. There are also three other waste water treatment plants operating in the commune area. Sanitary water drains for carrying waste-water from toilets, sinks, baths and household appliances have been installed in buildings of the settlements formerly belonging to the State Agricultural Farms. In the vicinities of the well site, sanitary drainage systems comprise the Obliwice and, in part, Łebień villages. In the remaining parts of the commune, domestic waste water is collected in leak-proof tanks to be transported subsequently to waste water treatment plants or discharged into fields or rivers in an uncontrolled way.

Communication and transportation

The Łebień well site is situated at intersection of a local gravel road and the Łebień – Rekowo Lęborskie district asphalt road no. 39316. The latter is a junction between the Łeba – Warlubie voivodeship road no. 214 and the Bąsewice - Rekowo Lęborskie – Łęczyce district road no. 39321) which links the roads with the Słupsk – Celbowo voivodehsip road no. 213 in the north. The Lębork – Choczewo – Wejherowo railway line, opened in the year 1910 and lately abandoned, is passing close to the drilling pad.

The motorway no. 6, forming the main connection between Gdańsk and *Szczecin.* that is between two main urban centers of northern Poland, passes in a distance of about 11 km (in straight line) from the Łebień well site. This is national motorway of GP class. The plans for the future include construction of a Trasa Lęborska motorway of S6 class as a section of Via Hanseatica, to create better connections between Russia and western Europe which will be important for development of all the southern coastal areas of the Baltic Sea.

The Gdańsk Główny - Stargard Szczeciński railway line, national line no. 202, passes parallel to the national motorway no. 6. This railway line is important in both domestic and international passenger and freight traffic.

The road network in the commune appears sufficiently dense. However, there are some limitations as several local roads do not have hard surface and, therefore, are not of much use under adverse weather conditions. It should be added that picturesque local roads, especially low-traffic ones, may be also adapted as tourist and recreation tracks for walking, cycling and horse-riding combined with enjoying the landscape. This is especially the case of local roads passing though forest complexes (*Studium…*, 2010).

Tourism and recreation

The studied area is moderately attractive from the point of view of tourism as tourist functions are still not fully developed in the Nowa Wieś Lęborska commune (Program…, 2008). According to the the Central Statistical Office data for the year 2009, the commune was offering all year round accommodation for 23 people only. In total, 1,370 visitors stayed in these lodgings for 1,658 nights which means that these stays were 1.2 night stays on the average.

The Nowa Wieś Lęborska commune has natural conditions favourable for the development of qualified tourism and agrotourism thanks to (see Studium…, 2010):

- a relatively short distance from the Baltic coast;
- significant share of areas of high natural value and attractive landscape;
- the already existing tracks for walking and cycling (regional cycling tracks no. 144, from Wejherowo to Lębork and Wicko, along district roads no. 1456, 1322, 1318 and no. 124, from Choczewo to Lębork and Bytów, along the district road no. 1322);
- the Łeba River – a tourist water route linking tourist-recreation areas of the Kaszubskie Pojezierze Lake District and Baltic coastal areas;
- attractive road and railway connections (national motorway no. 6, Gdańsk – Szczecin railway line and voivodeship road no. 214).

The Lubowidz Lake is of special importance for development of tourism and recreation in the commune. The lake, 168 ha in area, is situated about 9 km to the south of the Łebień drilling pad area. It is surrounded by forest and less than 100 m distant from the national road from Gdańsk to Szczecin. Numerous bathing places and recreational centers are situated around that lake.

Demography

The population of the Nowa Wieś Lęborska commune is about 13,000 according to data of the Central Statistic Office and Commune Office. The mean population density in the commune is 48 inhabitants per km^2 whereas in the whole Lębork district - 91 inhabitants per km^2 according to the above mentioned sources. The rate of natural increase is positive and high, equal 8 per mile in 2010. The net in-migration rate is also positive, equal 76 people. In the last 15 years the population of the commune increase by 1.431 (11%).

Almost 2,000 people live in 5 geodesic precincts localized in the 3 km radius from the Łebień well site.

Table 1. Demographic data for the vicinities of the Łebień well site.

No.	Geodesic precinct	Localities	Population	Population density [inhabitants/km^2]
1	Łebień	Łebień	975	74.14
2	Obliwice	Obliwice	203	35.55
3	Rekowo Lęborskie	Rekowo Lęborskie	245	23.79
4	Karlikowo Lęborskie	Karlikowo Lęborskie	90	33.21
5	Tawęcino	Tawęcino, Bąsewice	480	35.14

Source: Nowa Wieś Lęborska Commune Office, state as of 31.12.2009; za Studium …, (2009).

The share of the productive age group in total number of inhabitants equals 65%, being slightly higher that the medium value for the Lębork district (after data of Central Statistic Office). The share of the pre-productive age groupis higher than in the whole district (equal 24% and 21.7%, respectively). The share of registered unemployed in the total productive age group in the Nowa Wieś Lęborska commune is 12.3%, being higher than the average value for the district (9.7%) and the whole voivodeship (7%) (after data of Central Statistic Office).

2.5 Areas under legal protection and restricted and limited use lands

The Łebień well site is situated beyond any areas under legal protection. The site is situated far from any areas under legal protection. The closest Natura 2000 areas are 9 km distant to the east of the well site. They include:

- special protection areas of habitats of the Choczewskie Lake (PLH220096)
- Lasy Lęborskie special protection area of birds (PLB220006), the fragments of which are also under protection as a natural reserve (Długosz Królewski at Łęczyn) and protected landscape areas (Choczewsko – Saliński and Reda-Łeba proglacial stream valley protected landscape areas).

Protection areas of habitats also occur about 12 km to the north-west of the well site: Górkowski Las (PLH220045) (at the same time a natural reserve) and in similar distance to the south-west: Łebskie Bagna (PLH 220040) (Czarne Bagno and Łebskie Bagno natural reserves).

The Słowiński National Park is situated about 20 km to the north-west of the site but its protection zone comprises areas somewhat over 12 km distant from the Łebień well site.

The protected landscape area situated in 10 km distance to the east, south-east and south of the well site include:

- Choczewsko – Saliński Protected Landscape Area
- Reda – Łeba Proglacial Stream Valley Protected Landscape Area
- Łeba Valley Protected Landscape Area
- Protected Landscape of a fragment of the Łeba Proglacial Stream Valley with moraine hills south of Lębork.

The natural reserves situated the closest to the well site include:

- Górkowski Las and Nowe Wicko, situated about 12 km to the north-west; at the same time this is also Natura 2000 Górkowski Las special protection area of habitats ;
- Czarne Bagno and Łebskie Bagno, situated about 12 km to the south-west; at the same time it has also the stutus of Natura 2000 Łebskie Bagna special protection area of habitats;
- Pużyckie Łęgi, situated about 4 km to the east;
- Długosz Królewski at Łęczyn, situated about 9 km to the east; the same time this is also Natura 2000 Lasy Lęborskie special protection area of birds;
- Wielistowskie Źródliska and Wielistowskie Łęgi, situated about 12 km to the south-east.

Some trees from Tawęcino, the locality situated about 2.5 km to the north-east of the well site, have been given the Historic-Cultural Monument status. Such status results in prohibition to cut down or damage these trees as well as recommendations to take care of their appropriate exposition in the landscape, that is (*Studium*…, 2010):

- to preclude construction of buildings or other permanent facilities in 15 m radius from the tree trunk;
- to take care for tidiness of direct neighborhood (in the case of built-up areas),
- to leave natural vegetation around the monuments;
- to avoid installing linear elements of overground infrastructure in proximity of the monuments and laying down underground infrastructure within the extent of root systems of the monument trees,
- to prohibit stripping the monument trees of bark, leaves, buds and fruits.
- to prohibit removal of soil cover and lighting of fires.

As far as ecological utilities are concerned, the closest is situated at a distance of 7 km to the south-east, in direction of the Łęczyce village. Others are situated at a distance of 10 km to the east, within boundaries of the Choczewsko – Saliński Protected Landscape Area. Moreover, a numerous group of ecological utilities is situated in area of the Reda – Łeba Proglacial Stream Valley, in its meridionally oriented part, west of the Łeba River.

The ecological corridors recognized as of local significance but important for structure of the nature in the studied region include (Studium…, 2010):

- a strip related to the course of the Reknica and Lędziechowska Struga creeks (Łebieńsko – Kębłowska furrow),
- a strip related to the course of the Kisewska Struga creek.

Local ecological corridors are situated within about 2.5 km radius from the well site.

The following areas assigned to the ECONET network (Liro and others, 1998) are situated within 10 km radius from the well site:

- Reda – Łeba Proglacial Stream Valley: national ecological corridor;
- Baltic Sea coastland: international nodal area.

The planned forms of nature conservation in the studied region include (Studium, 2010):

- Łeba Proglacial Stream Valley protected landscape area;
- Lębork Landscape Park;
- ecological utility in swampy peat bog terrain 20.86 ha in area, plot no. 231, Redkowice geodesic precinct, Janowice Forest Inspectorate – at the proposal of Lębork forest authorities;
- ecological utility, an area close to Leśnice, situated in the Łeba Proglacial Stream Valley, the feeding grounds of the white stork;
- documentation site: a fragment of abandoned openpit workings in the vicinities of Lubowidz, with steep wall subjected to erosional processes and a floor from which water rises under high pressure;

and in the Lębork area (according to „Inventory and valorization of natural resources of Lębork town, 2001):

- Drętowskie Buczyny Natural and Scenic Complex;
- Dolina Świniuchy Valley ecological utility.

The course of boundaries of the protected landscape area and landscape park was proposed as element of the voivodeship concept of the nature conservation (Kostarczyk, Przewoźniak, 2001 r.). At the present stage, this is a preliminary proposal which requires making basic principles of protection more precise, drawing boundaries of areas in question and achieving some agreements. The final decision to establish the above mentioned forms of the nature conservation should be taken by the Voivode. In accordance with the law, new ecological utilities and documentation site may be established by the voivode or commune office.

As it was mentioned above, the studied region is situated beyond the extent of the major groundwater reservoirs. The Łeba Proglacial Stream Valley Major Groundwater Reservoir no. 107 is situated to the south of the Łebień well site and the Salino Intermoraine Reservoir no. 108 – at a distance of 5 km from the well side. Documentation of the two reservoirs has been completed before the year 2010 but decisions establishing their protection zones and enforcing prohibitions and limitations on land use were still not issued by the Director of the Regional Water Management Board.

Hydrogeological documentation of the Łeba Proglacial Stream Valley Major Groundwater Reservoir no. 107 has been approved by decision of the Ministry of Environmental Protection, Natural Resources and Forestry no. KDH 2/013/5914/96 on 30 September 1996. That documentation presented proposal to establish the Highest Protection Areas and those of High Protection for that reservoir because of shallow depth of occurrence of aquifer and the lack of sufficient isolation from the ground surface. The High Protection Area comprised Łebień village situated 3 km to the west of the Łebień drilling pad area.

Hydrogeological documentation of the Salino Intermoraine Major Groundwater Reservoir no. 108, completed in 2001, has been approved without reservations by the Department of Geology and Geological Concessions of the Ministry for Environment (notification no. DG/kdh/ED/489-6355a/2002 of 03 April 2002). According to that documentation, natural resistance of that groundwater body to pollution makes establishment of protection zone along the reservoir boundaries unnecessary.

3 Characteristics of hydraulic fracturing process

Shale formations perspective for occurrence of unconventional gas resources are represented by clastic rocks which exhibit extremely low permeability, below 1mD. In prospecting and exploration of shale gas resources it is necessary to carry out intensifying operations which would change parameters of rocks in the zone around the well bore, that is the process leading to an increase of permeability in the well section subjected to fracturing and, in this way, inflow of gas to the well bore. The hydraulic fracturing in horizontal sections of wells is currently the basic stimulation treatment routinely performed on both exploratory and production wells. The fracturing process results in origin of overpressure conditions in selected part of the rock massif and, in this way, origin of a penetrative system of fractures which open routes for migration of gas to the wellbore.

Hydraulic fracturing of rocks is a complex process. It consists of a number of different stages, generally a stage of propagation of fractures, that of introduction of a propant material (sand grains, ceramic or other particulates) to prevent the fractures from closing down when the injection is stopped, and the phase of removal of injected fluid. The whole process is continuously monitored using devices designed to control several key parameters of the operation, especially pressure of injection and amounts and density of the injected technological fluids, rates at which chemicals are added, concentration of propant material in the fluids, and pressure in borehole casing.

Hydraulic fracturing operations are connected with consumption of large volumes of water for preparation of technological fluids. This makes it necessary to store appropriate water reserves at the well site before the start of these operations. Therefore, two reservoirs with storage capacity of 6 000 i 12 000 m^3 (Fig. 4) were built in the Łebień well site area to secure water in quantities sufficient for performing the hydraulic fracturing treatments. These are upground reservoirs built partly above ground built by excavation in the ground and with embanked sides. The reservoirs were filled up with water obtained by pumping from water wells drilled next to them. The operator got water rights permit was for exploitation of 10 m^3/h so filling up the reservoirs lasted from spring to the mid-August 2011 to secure sufficient water reserves for the start of hydraulic fracturing treatments.

a b

Fig. 4. Water reservoirs localized in the Łebień well site area, a – reservoir no. 1, b – reservoir no. 2

The hydraulic fracturing was performed in the horizontal section of the LE-2H exploratory well on August 19-28, 2011. For carrying out hydraulic fracturing in a proper way, it was necessary to build an overground infrastructure comprising the above mentioned water reservoirs, a set of pump aggregates, storage tanks for proppant material, blender, manifold and numerous control and steering devices (Fig. 5). The fracturing was performed with the use of Coiled Tubing – flexible pipes making possible injection of technological fluids and hoisting probes and tools up and down the borehole. In accordance with Annex no. 1 to the Work Plan, hydraulic fracturing were performed on 13 intervals about 45-50 m in planned length, selected for perforation, fracturing and testing. Each interval was subjected to identical specialized treatment involving clean-up of what was left of the damaging material near well bore area, intensification of flow and sealing. The hydraulic fracturing of individual intervals was performed in 14 steps differing in length of time, quantity of injected fluid and type and proportions of addition of propant, in accordance with the accepted program.

Fig. 5. Line of pump aggregates ready for fracturing operations

The casing was perforated by firing explosive charges in all of 13 intervals. The major hydraulic fracturing was always preceded by acid wash treatment. This treatment was connected with injection of 8 m^3 of hydrochloric acid solutions to each interval of the well bore. These were 20% solutions of hydrochloric acid in the case of first intervals and 15% solutions in more distant ones. The solutions also yielded chemical additives to secure appropriate course of the fracturing treatment by dissolution of carbonate sediments, making the wellbore passable for fluids and removal of clay fraction, the swelling of which may block fissures and thus reduce permeability of rocks.

The above mentioned stage is followed by the major fracturing treatment, consisting in injection of appropriate volumes of the fracturing fluid into targeted rock layers in accordance with previously established program. Control of pressure under which the fluid is injected makes it possible to determine when fractures originate as this is reflected by pressure drop combined with simultaneous loss of fluid in surrounding rocks.

After origin of a network of fractures, fracturing fluids containing suspended proppants are injected under high pressure**.** The propants are represented by washed and graded high silica-content quartz sand with *s*pecific grain size and coated with resin. Their role is to prop open fractures in the rock formation and thus preclude the fractures from closing when pressure is removed. After injection of a predefined volume of fracturing fluids, water was pumped in under high pressure to “push” the fluids with suspended propants into the rock formation and then the well head was closed. The fracturing treatment of one interval lasted for about 2 hours.

The subsequent task was to isolate the treated zone from the next zone targeted for stimulation. Individual treated zones were isolated using isolation packers - devices for tight closing of well bore before moving to the next interval.

The above mentioned treatment were repeated in all the intervals, staring at the end and moving to the beginning of horizontal section of the well. From 1 181.73 to 1 744.47 m^3 of the fracturing fluid (water plus chemicals[1]) and about 100 Mg of propant at the average were used to stimulate individual sections. In total, 17 322.6 m^3 water and 462.09 m^3 of various chemical additives (representing about 2.5% of volume of the fracturing fluid) and 1 271.88 Mg of proppants were used in treatment of all the intervals. Table 2 presents detailed breakdown of volumes of water and chemicals and propant used in hydraulic fracturing of individual intervals of the well.

Table 2. Comparison of volumes of used water and other media in hydraulic fracturing treatment, with subdivision into individual intervals

Interval	Base fluid (water)	Chemicals	Fracturing fluid (water + chemicals)	Propant
	m^3	m^3	m^3	Mg
1	1519.60	40.44	1560.04	107.39
2	1175.56	34.35	1209.91	91.14
3	1247.72	40.39	1288.11	107.03
4	1515.11	32.63	1547.74	107.67
5	1157.30	34.56	1191.86	91.72
6	1302.39	39.79	1342.18	105.48
7	1274.65	37.91	1312.56	100.68
8	1310.61	40.87	1351.48	107.67
9	1199.81	32.77	1232.58	86.90
10	1152.23	29.50	1181.73	78.30
11	1419.28	27.55	1446.83	98.90
12	1706.17	38.30	1744.47	103.40
13	1342.17	33.03	1375.20	85.60
TOTAL	**17322.60**	**462.09**	**17784.69**	**1271.88**

After completion of hydraulic fracturing, that is after injection of fracturing fluid to all the stimulated intervals, packers isolating the intervals were drilled through. At this stage of the operation, about 10 m^3 of a polymer drilling mud based on water taken from the reservoirs was injected at each packer in the well bore. Drilling through each packer resulted in return of fracturing fluid in amounts close to the injected at a given stage, leading to equalization of pressure in the well. The returning fracturing fluids (flowback fluids) were subjected to treatment in settlement and filtration systems at the well site (see Chapter Technological Fluids, p. 43). After passing through that waste treatment installation, flowback fluids were disposed in already empty water reservoirs (see Fig. 4). The recycling of flowback fluids made possible their reuse in process of drilling through the packers.

[1] A detailed list of chemical additives is given in Annex no. 1 to the Work Plan of completion of the Łebień LE-2H exploratory well, approved by decision of Director of the Regional Mining Authority in Poznań (decision no. ł32/0234/0001/11/02193/KM of 12.04.2011.

The drilling through and removal of all the packers was followed by process of reduction of pressure gradient in the well to initiate inflow of gas. About 248 633,2 nm^3 (normal cubic meters) of nitrogen were pumped into the well, resulting in return of fracturing fluids and inflow of gas. All the treatments conducted for the needs of gas tests from 8 to 22 September gave 2780,7 m^3 of flowback fluids. Flowback fluids were subjected to purification at the drilling pad in installation consisting of separators, settling tanks and filters and discharged into the open-air reservoirs formerly used for storage of technical water. When operations at the Łebień LE-2H well were completed, the fluids stored in the reservoirs were transported for reuse in hydraulic fracturing at other well site.

After completing stimulation processes, gas and production well testing was performed (Fig. 6) and the well was shut in.

Fig. 6. The Łebień well site during gas tests

The hydraulic fracturing performed in horizontal section of the Łebień LE-2H well, carried out within the frame of exploration of shale gas, was the pioneer treatment performed in Poland. Therefore, these operations were subjected to careful assessment from the point of view of potential impact on individual components of the natural environment. The results of that assessment are presented in the present report.

4 Identification of potential risks

Theoretical routes of migration of pollutants

The assessment of environmental impact of the hydraulic fracturing treatment made it necessary to analyze all the stages of operations performed on well, from preparatory works to those connected with well shut-in. The stages of the treatment operations most important from the point of view of the environment protection were defined along with the scope and preliminary time table of research and exploratory works. This made it possible to point out potential ways and possibilities of migration of pollutants in the well site region. The analysis covered all the possibilities (including even most remote ones) of potential migration of pollutants to the environment, that is to air, soil and surface and ground water. Three potential possibilities of migration of pollutants were identified in the course of technical analysis of the fracturing operations (Fig. 7). These are:

1. Migration of liquid and gaseous pollution from the horizontal well section to water-bearing horizons along privileged circulation routes;
2. Migration of liquid and gaseous pollutants from the well pad area to water-bearing horizons and the land surface;
3. Migration of pollutants from the land surface to soil and, subsequently, towards water-bearing horizons.

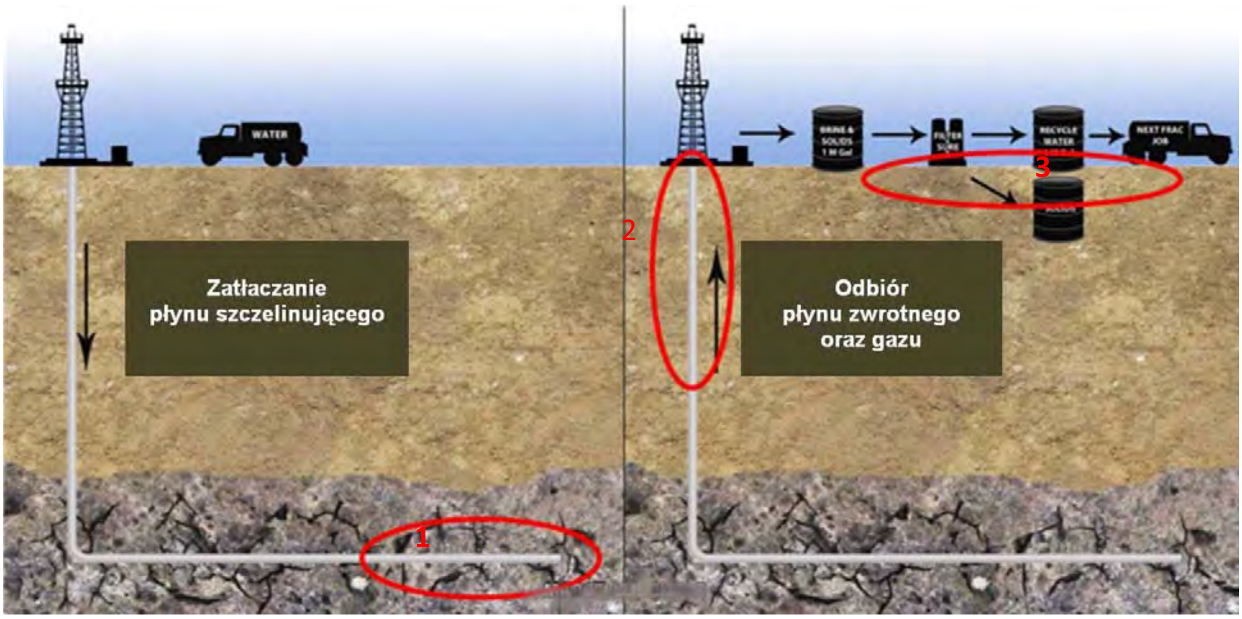

Fig. 7. Scheme of hydraulic fracturing treatment and potential router of migration of pollutants (1 – migration From horizontal well section, 2 – migration along well casing, 3 – migration from the land surface)

Taking into account almost 3 000 m thickness of rock series isolating the shale formation subjected to stimulation from usable water-bearing horizons and land surface, possibilities of migration of potential pollutants from the fracturing fluid or gas escaping from the stimulated rocks of the shale formation seem rather remote. Such migration would require existence of privileged circulation routes such as deep tectonic zones or improperly filled and sealed wells. The analysis of the available data show that such privileged circulation routes are missing in the Łebień LE-2H well site (see **Possibilities of migration of shale gas,** pp. 21-23) so potential migration routes of these types were not taken into account in further studies.

The possibilities of migration of pollutants along vertical section of a well column should be taken into account only when a protective cement sheath around casing was improperly set or fractured. However, placing of a cement sheath isolation around well casing has to be closely monitored throughout the fracturing treatment operations and gas tests both for safety and economic reasons. Therefore, it may be assumed that environmental pollution of such type may take place in the case of a technical failure or human error only. In both cases information about the accident would be known before any pollutants reach the land surface or water-bearing horizons.

The third possibility is related to migration of pollutants from the land surface to soil and surface and ground water along with surface wash and rain water infiltration through the soil. Taking into account the specific character and complexity of the fracturing process, that is:

- use of large amounts of fuels and chemicals;
- necessity of storage and mixing them in the well pad area;
- work under very high pressures;
- necessity to handle, store and secure large volumes of fracturing and flowback fluids;
- use of open-air earth reservoirs and tanks of various types;

and additional potential risks as those related to:

- sanitary sewage;
- rainwater running off surfaced technological yards into local ponds and soaking into the ground;
- high traffic volumes of heavy construction vehicles in the well sites area;

the risks of environmental pollution appear real. Therefore, the present study was aimed mainly at assessment of potential risk of pollution of the land surface and groundwater from the these sources.

Possibilities of migration of shale gas

On the basis of rich experience from production of conventional gas in Poland, especially in the area of the Carpathian Foreland, it may be assumed that in the case of shale has resources the highest risks of methane emissions would be related to (Ciechanowska and others, 2008):

- gas escape through natural fissures or fault zones,
- improper construction of well, resulting in leaks through or between well casing strings or along the well column.

Recognition of internal geological structure and structural development of an area selected for exploration should be aimed at most precise identification of presence and course of zones naturally predisposed to act as migration pathways for gas.

Archival material on the Lębork concession area, coming from the times before the concession has been issued, comprises several borehole data reports (packages?) on deep drillings and nonuniformly distributed 2D seismic lines (Fig. 8). The majority of wells localized in the Lębork concession are reached top of the Silurian but did not enter the formations most perspective from the point of view of exploration for resources of the shale gas type, that is the Lower Silurian (Llandovery) and Ordovician. Only two of these deep wells from direct neighborhood of the Łebień LE-1/2H wells reached the latter formations and provide relevant information. These are the Lębork

IG-1 well, situated about 10 km to the south-west of the Łebień well site, and Lubiny-1 well, situated about 14 km to the north.

The coverage of the Lębork concession area by seismic lines is very unequal (Fig. 8). All the reflection seismic lines acquired in the years 1992-1994 by Geofizyka Toruń Ltd. at the order of Polish Oil and Gas Company S.A. (PGNiG S.A.) for the needs of exploration for conventional hydrocarbon resources are localized in northern part of the concession area. The exploration and seismic surveys primarily targeted sandy rocks of the Middle Cambrian. A few of these seismic lines (as for example T0230194, T0330194, T0350194, T0380194) run through the area stretching 5 to 7 km to the north of the Łebień LE-1/2H wells (Wilk, 1995). .

The seismic line running to the south-west of the Łebień LE-1/2H wells (GBB10387 line) was acquired within the frame of the Deep Seismic Surveys Program, Lębork region, conducted by the Polish Geological Institute and PBG Geophysical Exploration Ltd. (Białek and others, 1991). The surveys were aimed at studying lithosphere structure by the seismic reflection method. However, the obtained data turned to be generally of rather poor quality. Relatively good results (although of much poorer quality than in reflection seismic surveys run for exploration for conventional hydrocarbon resources) were obtained for the Zechstein-Mesozoic complex. In turn, only a few traceable seismic horizons were recorded in the sub-Zechstein successions which are the target of the current exploration. Therefore, data from the GBB10387 seismic line are of negligible importance for exploration targeting resources of the shale gas type.

The above mentioned reflections seismic lines acquired in the early 1990s by Geofizyka Toruń Ltd. at the order of PGNiG S.A. run at too large distance from the Łebień LE-1/2H wells to state whether or not the wells are situated at or in direct proximity of any fault zones.

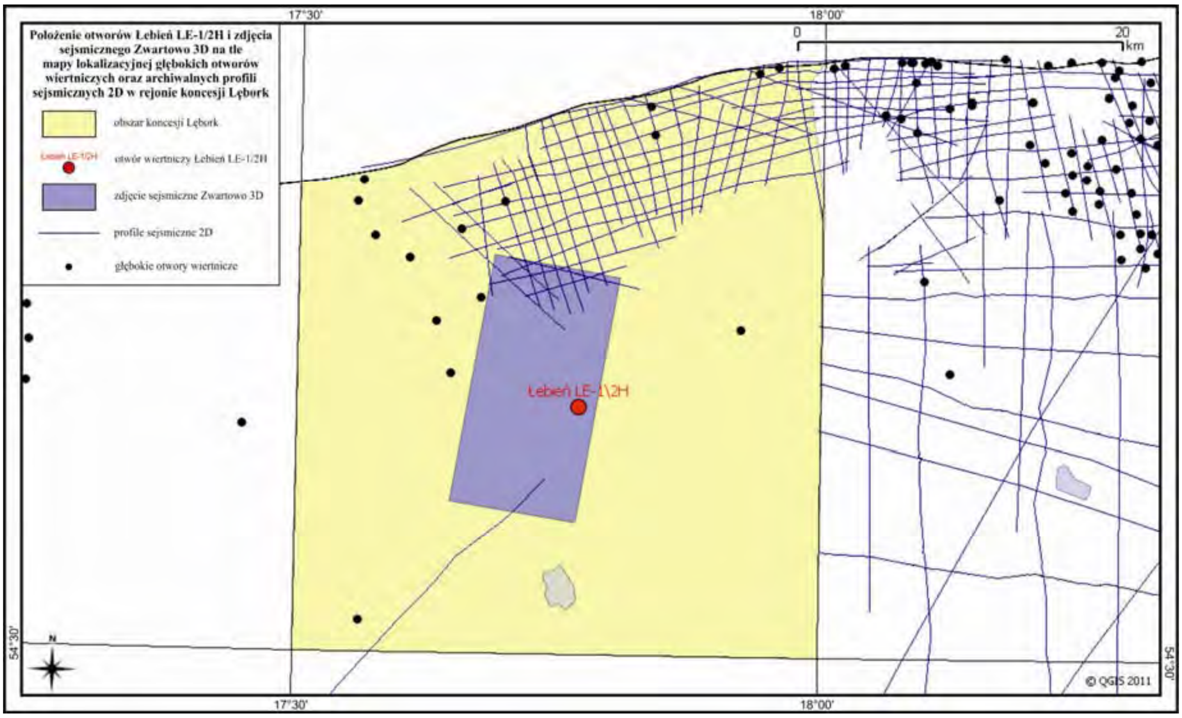

Fig. 8. Location of the Łebień LE-1/2H wells and Zwartowo 3D seismic surveys at the background of location map of deep boreholes and archival 2D seismic lines surveyed in the Lębork concession area

The latest seismic data were acquired in the Lębork concession area in the second half of 2009 by Geofizyka Toruń Ltd. at the order of Lane Energy Poland Ltd. The data were gathered within the frame of the Zwartowo 3D seismic survey covering an area of about 125 km^2 and aimed at structural and tectonic analysis of Lower Silurian and Ordovician formations (Fig. 8).

According to recently published structural map of the Cambrian which comprises the Łeba Elevation (Domżalski and others., 2004) (Fig. 9), the Łebień LE-1/2H wells are situated a a distance of about 3 km to the north from the nearest fault zone. However, it should be remembered that it is a regional map with limited accuracy as for requirements of precise structural and tectonic analyses. This is especially the case of areas such as the central and southern parts of the Lębork concession, where both deep boreholes and seismic lines are missing. This makes it necessary to trace presence of tectonic zones on the basis of gravimetry data.

To sum up, the lack of access to the latest seismic data acquired in the well site region precludes any unequivocal identification of presence and course of fault zones which could act as potential routes for migration of gas and fluids. However, the results of analysis of the above mentioned structural map of the Cambrian and the fact that the concession holder decided to order the Zwartowo 3D seismic surveys aimed mainly at selection of the most suitable location of the first test exploratory well and consciousness of risks which would bring location of such wells in direct proximity of a fault zone for further works make it possible to assume that the Łebień LE-2H well is situated at a safe distance from any fault zones.

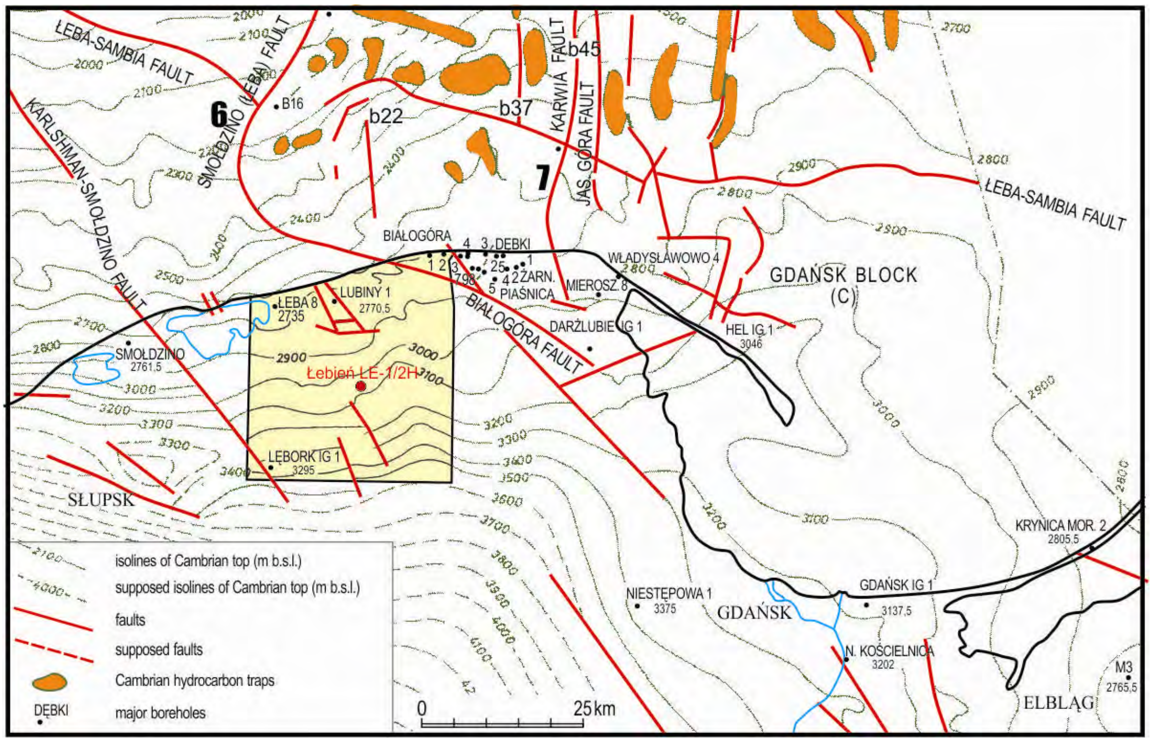

Fig. 9. Location of the Łebień LE-1/2H wells at the background of structural map of the Cambrian (after Domżalski and others, 2004) in the Lębork concession area

Seismic events

Earthquakes are very rare in Poland. The Łebień well site is localized in area of tectonically stable East European Platform.

In the last few years there appeared numerous reports linking earthquakes with shale gas production, especially in the United States and Canada. More recently such reports came from Great Britain (Annex no. 10) where quakes with magnitude of 2.3 and 1.5 have been recorded in south-west England in April and May 2011. A report compiled by seismologists and geologists stated that there is high probability that these quakes were induced by hydraulic fracturing operations performed in the course of exploration for shale gas resources (Baisch, de Pater, 2011).

At the same time the report states that the quakes were induced because of complex and specific geological conditions in the well site area. Moreover, the risk of occurrence of the next strong quakes was said to be rather unlikely.

Gases and dust

The following pollutants may be emitted to the air from area of the well site:

- natural gas escaping in result of lack of tightness of the well bore zone,
- sulfur dioxide originating in combustion of diesel fuel in internal combustion engines,
- nitrogen dioxide originating in combustion of diesel fuel in internal combustion engines,
- carbon monoxide accompanying other products of combustion of diesel fuel in internal combustion engines,
- benzene as a product of incomplete combustion of diesel fuel in internal combustion engines,
- other hydrocarbons as products of incomplete combustion of diesel fuel in internal combustion engines,
- elementary carbon in the form of soot as a product of incomplete combustion of diesel fuel in internal combustion engines.

Natural gas is composed mainly of methane (95%), which may be accompanied by carbon dioxide, nitrogen as well as small amounts of hydrogen sulfide and admixtures of some other hydrocarbons. Low concentrations of hydrogen sulfide in the air give characteristic foul odor whereas in higher concentrations it is toxic and poses a serious health risk to humans and animals. Hydrogen sulfide easily undergoes oxidation to far less toxic sulfur dioxide in the environment and is transformed chemically into non-toxic sulfates in water medium. According to representatives of the investor, hydrogen sulfide does not occur in gas from the Łebień LE-2H well.

The exploration for gas resources by drilling involves the use of high-power internal-combustion engines run on diesel fuel. Such engines emit exhaust gas in amounts proportional to the of fuel consumed. The engines installed at the well site are used when needed only.

An increased dust emission may be expected during drilling and well stimulating operations. However, dust emissions from agricultural operations clearly predominate in the Łebień LE-2H well, especially in summer. Therefore, the eventual emissions from the hydraulic fracturing treatment would not be easy to identify and their scale not comparable with that of dust from agricultural operations.

Noise

The dominant sources of noises are here diesel engines and high power pumps used in drilling and hydraulic fracturing treatment operations in the well site area. The wheeled traffic connected with delivery of materials and transport of installations for the well site also acts as a source of significant noise different of that typical for farmland with poor quality asphalt roads. All other activities connected with exploration for shale gas do not represent a significant source of noise pollution.

Waste management

Wastes originating in the course of hydraulic fracturing treatment appear diversified in amounts and properties and, therefore, the scale and type of their impact on the environment.

The total volume of waste from the fracturing operation represents only a small per cent of those originating in the drilling operations.

The flowback fluid is the major component of waste stream from fracturing operations. The fluid yields small amounts of unused proppant which, nevertheless, form the bulk of dry mass of the waste. Contrary to common belief, the flowback fluids do not carry up to the surface any significant amounts of autochtoneous material from the fractured zone as the fluids cannot get inside pipes of the well bore casing. However, the fluids may carry heavy loads of chemicals originally used as components of fracturing fluids as well as those dissolved or leached from the fractured rocks. Bituminous shales yield up to 25% of organic matter and, therefore, sulfur and nitrogen compounds and heavy metals including mercury, cadmium, zinc, lead, copper, arsenic, nickel, chromium, cobalt and vanadium and sometimes radioactive elements. In the major part these compounds are practicably insoluble in water under normal pressure and temperature conditions. The pressure and temperature conditions prevailing at over 3 000 m depths may facilitate partial solution of some of those compounds but they precipitate again as suspension load when brought to the surface.

The waste from fracturing operations yields also some chemical matter mobile in the environment. This is especially the case of sodium and chlorides, mainly of anthropogenic origin as coming from previously used drilling mud. However, no results of analyses of chemical composition and physical properties of waste from fracturing operations performed in Poland are available yet.

The major aim of appropriate management of waste from fracturing operations (besides adhering strictly to the environmental legislation) should comprise diminishing waste mass by more effective separation of solid parts from technological water. This will make possible reduction of solid waste stream which comes back to the environment as well as reuse of technological fluid and, in this way, protect water resources and save energy needed for their exploitation.

Radioactivity

Natural radionuclides are omnipresent on the Earth and their radiation along with the cosmic one form background radiation*, that* is the ionizing radiation constantly present in the *natural* environment and constantly affecting all the living organisms.

In Poland, radioactivity of rocks of the shale gas formation has been measured in borehole core material obtained in the course of exploration for shale gas in the Lublin and Pomeranian voivodeships (the Markowola-1 and Lubocino-1 wells, respectively) (Sojski, 2011a, b). The studies showed that potential gas-bearing rocks from depths of 3 500 – 4 500 m are characterized by low level of radioactivity. The rocks even match strict requirements which should be met by raw and building materials used in construction of houses and farm buildings for animals as defined by requirements enforced by the Regulation of the Council of Ministers of 2 January 2007, concerning the content of natural radioactive isotopes of potassium K-40, radium Ra-226 and thorium Th-228 in raw materials and materials used in buildings designed to accommodate people and livestock, as well as in industrial waste used in construction industry, and the procedures for controlling the content of these isotopes (Journal of Laws of 2007, no. 4, item 29).

Even if rock formations regarded as shale gas exploration target in the studied region are characterized by increased level of radioactivity in the studied region, the eventual risks would not be related to these rocks but rather radioactive decay products *brought* to the surface by the circulating drilling mud and flowback fluids. Radon may be such product as it is easily soluble in water. The radon radionuclide most important from the point of view of environmental impact is isotope ^{222}Rn. This is a product of a chained ^{238}U decay series of transformations. It is a noble gas a few times heavier than air, colorless, odorless and tasteless under normal conditions. It has a half-life of 3.8 days.

In Poland, radon recorded in air mainly comes from emanations from uranium-rich Scandinavian erratic material occurring in Quaternary glacial sediments. However, there are reports of radon emissions along deep tectonic dislocation zones in some places in the world. When this is the case, we would be dealing with migration of the diffusion nature, resulting mainly from a pressure gradient. Analogous phenomena may theoretically take place when a formation of rocks enriched in uranium becomes open by well bores, especially horizontal ones. When this is the case, easily soluble radon may migrate along with flowback of technological fluids. However, radon levels in soil gas may reach the level of thousands Bq/m^3 even without contribution of gas migrating from large depths. The level of radon emission from soil depends on place (type of soil and geology of substratum) and atmospheric conditions (atmospheric pressure, wind strength and direction, humidity) so concentrations of that gas in soil may be subjected to seasonal and even daily variations.

Serious technical accidents and natural hazards

The area of the Łebień drilling pad is safe from natural disasters as floods, tsunami and earthquakes. The risk assessment for the Nowa Wieś Lęborska commune shows that potential hazards capable to evoke crises include fires and unforeseeable weather conditions such as hurricanes or torrential rains.

The site accidents may take place in the course of fracturing operations on a well due to unforeseeable geological conditions, human errors or violations or equipment failure. The Łebień LE-2H drilling pad is situated far away from any settlement and, therefore, effects of such accidents should not be arduous for the local population. Similarly, the environmental impact should be negligible due to possibility that emergency measures can affect *an* accident's outcome are quickly taken.

5 Identification of environmental elements exposed to influence

Air

An impact study was performed by the Gdańsk Voivodeship Inspectorate for Environmental Protection in the Nowa Wieś Lęborska commune to assess air quality effects resulting from operation of the Łebień LE-2H well. Air quality analyzes carried out by the method of p*assive* monitoring of *nitrogen dioxide* showed that actual concentrations of pollutants are markedly lower than the permissible maximum. Aerosanitary conditions are good throughout the major part of the commune thanks to relatively small number and usually very limited arduousness of local sources of air pollution and wind patters which help cleanse the air. Higher but still permissible concentrations of gases and dust may occur sometime in direct neighborhood of emittors (especially in the Nowa Wieś Lęborka and Lębork areas) but they are due to tropoclimatic conditions and do not pose any significant *risk* to *human* or *animal health.*

The Łebień drilling pad is situated in farmland, far away from any areas of concentrated village settlements. The closest are settlements of the Karlikowo Lęborskie village, in a straight line about 500 m distant from the well site. The well site is surrounded by a farmland put under crops of rape, wheat and rye in the season of 2011. Under these conditions, gas emissions from drilling operations may change *atmosphere composition* by introducing gases not occurring in the nature in that region and increase concentrations of gases from fuel combustion in village households and increase concentrations of those typical of a*utomotive* exhaust emissions. Moreover, high-power diesel engines *used* for *well site* work may also increase concentrations of airborne dust.

Landscape

The Łebień drilling pad is situated in agricultural area, by the road along which *grow bushes* and trees. This area appears to be of rather low landscape value.

The drilling activity introduced very noticeable changes in the landscape. This was especially the case of view of the drilling rig in action, much easier to remember than infrastructure used in the fracturing treatment. However, these changes were only temporary. The traces which will remain for some more time are earth banks around the drilling pad and two partly upground reservoirs for storage of technological water and also (as of October 2011) a well head with a system of control valves and devices.

Land surface, soils

The pression exerted by drilling operations on the land surface is mainly connected with compaction of subsoil layer (soil is understood here as upper organic layer usually removed over an entire surface area and heaped to form a bank acting as a fence around the drilling pad) due to long-term loading. The pression is also connected with possibilities of pollution by chemicals used in drilling works and well bore stimulation operations (here hydraulic fracturing) and fuel used by vehicles. The pression is exerted also on adjacent areas, for example those used as parking space for delivery trucks and passenger cars. Moreover, heavy truck loads can damage hard-surfaced local roads and *traffic arteries.*

Because of specific character of the hydraulic fracturing process it is theoretically possible that the treatments may result in origin of seismic quakes perceptible at the land surface.

Surface waters

The Łebień drilling pad is situated in drainage basin of the Łeba River which flows into the Baltic Sea. The surrounding area directly adjacent to the well site is not drained by any water creek. However, potential pollution from the drilling pad may migrate through a system of drainage ditches to the Kisewska Struga creek which is direct tributary of the Łeba river.

Groundwater

The risk of groundwater contamination by pollutants leaching from land surface is the highest in the case of the shallowest Quaternary aquifer, used here as the major usable water-bearing horizon. In the Łebień well site area, that aquifer has a free water table located at depth of 15 m below the land surface. A largely *impervious* layer of tills which covers and separates the Quaternary *water-bearing* sediments from the surface is here rather thin (about 3 m in thickness), resulting in increased vulnerability of this aquifer to contamination. According to regional studies, it would take about 30 years for eventual conservative pollution to soak from the land surface into the first water-bearing horizon. In the case of the Łebień drilling pad area that time may be shorter due to small thickness of isolating sediments. After reaching water-saturated zone the pollution would migrate in direction consistent with regional water flow, that is to the south and south-east.

Human factor

Activities connected with exploration for shale gas resources raise the level of public anxiety and tensions. This is due to several factors including rise of public awareness of potentially adverse effects of shale gas exploration, the lack of exhaustive technical information on these operations and processes used in these works and finally contradictory public values and interests. All these factors may turn to be root causes of social conflicts.

Since some time the issues connected with shale gas exploration have become an increasingly hot topic in the media. Coverage of these issues has often tended to focus on sensational and in large part unconfirmed examples of especially harmful impact of shale gas exploration and production on the environment and human health. The news stories have so far proved difficult to verify and, therefore, some residents of areas of planned exploration became distrustful or reluctant and not want drilling pads anywhere near where they live.

A few significant protests against shale gas exploration and production have taken place in Poland. In opinion of people involved in these conflicts, the major problems include the lack of public consultations and decent information provided well in advance.

6 Scope of studies and spatial extent of the analysis

The process of hydraulic fracturing treatment on the well and its individual stages from preparatory works to securing the well were analysed for the needs of studies on environmental impact of these operations. Major stage of the operations were identified to define the scope and preliminary time table of the studies. The detailed time table and scope of individual stages of works and studies are given in Table 3.

Table 3. Time table of works carried out at the Łebień LE–2H drilling pad

Dates	Stages of work at Łebień drilling pad	Stages of studies of the research team
13.06. - 18.07.2011	End of drilling, drilling rig dismantling	Stage I – site inspection, analysis of available materials, preparation to the studies
19.07 - 31.07.2011	Drill site preparation for starting fracturing treatment	Stage II – defining background for analyses of impact on air, land surface, surface and ground water; start of seismic surveys
01.08. - 18.08.2011	Transport and assemblying equipment for fracturing, safety tests	
19.08 - 28.08.2011	Conducting fracturing treatment	Stage III – measurements of concentrations of air pollutants and noise level, seismic surveys, sampling ground water and technological fluids for laboratory analyses
31.08 - 07.09.2011	Drilling out the plugs, pressure reduction well bore	
08.09. - 22.09.2011	Production tests. Injecting nitrogen	Stage IV – analyses of soil gas, sampling shale gas, measurements of emissions, sampling ground water and technological fluids, chemical analyses of ground water samples, chemical and toxicological analyses of samples of technological fluids
23.09. - 13.10.2011	Dismantling equipment, securing well and well site, waste disposal	Stage V – sampling groundwater and technological fluids, continuation of chemical and toxicological analyses of sampled groundwater and fluids, analyses of soil gas samples, continuation of measurements of soil and air emissions

The studies were carried out by research teams from several scientific institutions and civil services, in accordance with their competence and profile of activity. The studies were coordinated and supervised by the Warsaw-based Polish Geological Institute –National Research Institute.

Monitoring of seismic events

The seismic monitoring of the fracturing treatment from its second stage to the fifth see Table 3) was conducted by the Institute of Geophysics of the Polish Academy of Sciences within the frame of the „Monitoring of seismic hazards in area of Poland" Project. Seismic surveys were carried out from 15 July till 30 September 2011 which made it possible to *measure* the *magnitude of seismic disturbances* before the start and during hydraulic fracturing treatment and to record eventual seismic events which would occur with some time delay. Ten mobile seismic stations were used in these surveys. The stations were located at distances ranking from 1 to 25 km from the well site (location of the stations as given in Annex no. 10).

Air

Measurements of concentrations of gaseous pollutants in air and noise levels were taken by the Voivodeship Inspectorate for Environmental Protection in Gdańsk. It was decided not to measure concentrations of airborne dust as that *indicator* is *not specific* for the purposes of this study and due to predominance of dust emissions coming from other sources than the Łebień drill pad installations. Location of measurement points is given in Annex no. 1.

The indicators selected for assessing potential pollution included: sulfur dioxide, nitrogen oxides, benzene, methane, carbon monoxide and hydrogen sulfide. Measurements were taken by the calometric method using Draeger CMS mobile analyser (Fig. 10). The series of measurements were taken three times at three measurement points on July 19, August 19 and September 30, 2011. The obtained values were converted to normal conditions ((temperature of 0^{o} C - 273,15 K, pressure of 1013.25 hPa).

Fig. 10. Measurements of concentrations of gaseous pollutants in air in area of the Łebień drilling pad

The measurements were supplemented with those made using the passive measurement method which makes it possible to determine much lower concentrations of selected indicators of air pollution. Indicators selected for these studies included sulfur dioxide, nitrogen dioxide and benzene. The passive measurement method is connected with continuous sorption of pollutants from air throughout one month exposition. The samplers were installed two times: in August – September and October - November 2011.

Measurements of noise level were made at three measurement points in order to trace changes resulting from emission and propagation of sound waves in the studied area (Fig. 11). The report presents averaged results of series of measurements.

Fig. 11. Measurement of noise level at the *nearest* residential *property* (measurement point no. 3)

Radioactivity

In order to check hypothesis of potential health risk due to migration of radon from the shale formations, the PGI-NRI team measured concentrations of radon (^{222}Rn) in soil gas on July 19 and 20. The measurements were taken at the Stage II of the studies, that is before the start of the hydraulic fracturing treatment. They were repeated at randomly selected points on October 13 within the frame of the Stage V of the studies.

Measurement points of the first series were arranged in a *network of* squares with sides of 100 m and 24 points situated outside the drilling pad area. Five additional points were located at the drilling pad, with the central one placed next to the well head. Location of measurement points was determined in the field by the azimuth-step method with the use of topographic maps in the scale 1:10 000.

The studies covered an area of about 17 ha. Some points had to be shifted in relation to location in the designed measurement network because of topography of land surface and resulting difficulties for taking samples.

Soil gas samples were taken using drive *samplers* (Fig. 12) pushed into the *soil* down to 0.8 m depth. Such sampling depth was chosen due to the following reasons:

- influence of daily fluctuations of weather conditions (pressure, air humidity, wind power, daily temperature oscillations in a given season) is so small that it may be neglected;
- the depth of 80 cm ensures that inflow of atmospheric air to the soil gas sampler is blocked and the studied sample fully represents emanations coming from geological substratum.

The collected samples of soil gas, 150 ml in volume, were analysed using Radon Detector LUK-3B portable device. The soil gas samples were introduced to so-called Lucas cell of that device with the use of a siringe. Subsequenty the device automatically takes measurements and processes the obtained results. The processed results show concentration of radon in soil gas in kBq/m3, where one becquerel is defined as the activity of a quantity of radioactive material in which one nucleus decays per second.

Fig. 12. Soil gas sampler and probe

The second series of measurements was aimed at comparison of data on concentrations of radon in soil gas before and after the fracturing treatment. The number of measurement points of that series was limited to 7 (6 points outside and one point inside the drilling pad area). Location of these points was consistent with the measurement points network designed for the first series. This time the individual measurement points were about 200 m distant from one another. The methods of sampling and analysis of soil gas were the same as used in the first series of measurements. Measurements of concentration of radon in (^{222}Rn) soil gas were taken at the points no. 6, 8, 10, 14, 20, 22 i 24 (see Annex no. 1).

Possible shale gas exhalation

In order to document the environmental state before the start of the fracturing treatment operations (Stage II), the PGI-NRI team took measurements of methane concentrations in soil gas. The measurements were conducted using Seitron portable methane detector and a set measuring devices its own construction (Fig. 13). The measurements were taken in areas with natural predisposition to increased concentration of methane of biological origin such as waterlogged meadows, depressions without drainage and floodings on 19 – 20 July 2011. Measurement points were selected with reference to air photos, topographic maps in various scale, geological map in the scale 1: 50 000 and results of site inspection. The points are situated within a 5 km radius from the drilling site. Additional measurements were taken at the points of the radon measurement network around and inside the drilling pad. Location of the measurement points is shown in the documentation map (Annex no. 1). The method used in soil gas samples was the same as in studies on concentration of radon.

Moreover, a point of methane concentration in aeration zone measurements was installed within the drilling pad area in the Stage II of the studies. A small thickness of confining sediments (tills) in comparison with over 10 m thickness of the aeration zone (various-grained sands) made it possible to install filter of the direct well type in the aeration zone. The monitoring well was used to take measurements of methane concentration at all the subsequent stages of the studies carried out in the drilling pad area. That well was not closed but secured which makes possible taking measurements in the future.

Fig. 13. Set of devices for measuring methane concentration in soil gas

Directly after completion of the fracturing treatments the specialists from the Oil and Gas Institute in Cracow used the above mentioned measurement points to take soil gas samples for laboratory analysis of chemical composition and isotopic ratios of carbon. They also took two gas samples from the Łebień well to compare characteristics of shale gas and organic compounds from soil gas. The studies were aimed at stating whether or not the shale gas appeared in the soil gas and give comparative material for such comparisons in the future. The detailed scope and methodology of studies carried out by the the Oil and Gas Institute in Cracow are given in Annex no. 11.

Technological fluids and waste

During the fracturing treatments (Stage III) and gas tests (Stage IV), the Warsaw team of thePGI-NRI conducted analysis of the technological process, collecting data on volumes of water used in the treatments and monitoring quantity and quality of water stored in the technological reservoirs. Samples of the injected fluids – hydrochloric acid (Fig. 14) and fracturing fluid – were taken for chemical and toxicological laboratory analyses. Direct sampling of the fracturing fluid was not possible due to the fact that its final mixing takes place in the high-pressure part of the installation. The technological line is designed in such a way that one part of pumps is transporting double concentrate of fluid with added chemicals and proppants and the second – technological water without any additives. Fluid is subsequently mixed with water at a 1:1 ratio Therefore, two samples were take: one of concentrate of fracturing fluid with addition of quartz sand and another – of technological water. For the purpose of further analyses, the samples were mixed at the same ratio (1:1).

Fig. 14. Taking samples of hydrochloric acid from acid bath for laboratory analyses

Along with the start of process of drilling out the plugs separating individual fracturing intervals, the team began sampling raw fluid coming back from the well bore (flowback fluid) and fluid subjected to treatment (Fig. 15).

Fig. 15. Taking samples of raw flowback fluid for laboratory studies

Fluid samples were taken directly after drilling out the plugs no. 3 and 6 and subsequently on the first day of appearance of gas in the well bore, on the tenth day (when the circuit of nitrogen injection to the well bore became reversed) and on the last day before closing the well. Each time both there were taken samples of both raw fluid and fluid treated before discharge into the technological reservoir. There were also taken samples of fluid from the reservoir in which flowback fluid was stored after treatment. This sampling program was aimed at assessing chemical properties of flowback fluid and results of treatments conducted for making possible its proper management. At the same time the quantity of flowback fluid was estimated and water balance compiled for whole operation of the fracturing treatment performed on the well.

Chemical analyses of the collected samples of fluids were performed in the PGI-NRI Central Chemical Laboratory in Warsaw, and ecotoxicity analyses – by the Biology Division of the Faculty of Environmental Engineering of the Warsaw University of Technology. The detailed range and methodology of ecotoxicity analyses are given in Annex no. 12.

In order to evaluate the waste management and effectiveness of individual activities, the PGI-NRI specialists gathered programs of management of drilling and hazardous waste implemented by the Lebień well operator. The specialists also carried out site inspection of recultivated solid *waste* disposal facility at Lucino (Wicko commune) where the waste from fracturing operations were directed in accordance with the above mentioned programs. During that site inspection, the specialists analysed technology of use of the waste in recultivation of the disposal facility and reviewed documents confirming reception and quantities of the waste brought from the Łebień drilling site.

Surface waters

Analyses of quality of surface waters were conducted by the Voivodeship Inspectorate for Environmental Protection in Gdańsk. Sample collecting site was established on the Kisewska Struga creek, downstream of Brzeźno Lęborskie (location as given in Annex no. 1). The analyses of quality of water in the Kisewska Struga creek were made by the Voivodeship Inspectorate for Environmental Protection Laboratory in Gdańsk. Samples were taken three times: on 19 July, 30 August and 20 September 2011 (Fig. 16). The pollution indices selected for the studies included: pH, dissolved oxygen, BOD_5 (biological oxygen demand in five days), chlorides, sulfates, sodium, potassium, sum of nitrate and nitrite nitrogen, Kjeldahl nitrogen, total nitrogen, TOC (t*otal organic carbon*), sum of C_{10} – C_{40} hydrocarbons, boron, detergents (anionic and non-ionic) and sulfides.

Fig. 16. Surface water sampling

Groundwater

The PGI-NRI carried out studies on impact of the hydraulic fracturing treatment on ground water in the Łebień LE-2H well region from the time of completion of the well (June 2011) till the end of production tests in the well bore. This time period made it possible to document background state of the environment when the well was completed and the fracturing operations were still at the preparation stage, to conduct studies during the fracturing treatment and production tests and analyse ground water parameters directly after completion of all the works in the well bore and at the drilling pad.

The first stage of the studies was devoted to collecting data and information needed for characterizing hydrogeological conditions in this region and analysis of the range and type and the planned fracturing treatment. The team also carried out site inspection of the studied are, including the drilling pad. Moreover, the team carried out hydrogeological mapping of an area within 2 km radius from the drilling pad, involving identification of hydrogeological objects and measurement of water table depth. Moreover, all the hydrogeological objects identified in this area were evaluated from the point of view of possibility to take water sample for physico-chemical analysis. In total, 17 drilled water wells and 3 hand-dug wells were mapped and evaluated. Measurements of water table depth were made in 5 drilled and all the hand-dug wells. Information on identified hydrogeological objects is summarized in the Annexes no. 8 and 9 and their location is shown on the documentation map (Annex no. 1).

The collected information (archival data stored in the Central Bank of Hydrogeological Data and database of the Hydrogeological Map of Poland in the scale 1:50 000) and results of field work were used in modeling ground water flow in the region of the Łebień LE-2H well. Construction of mathematical model and the course of works were adjusted to the major goals of the modeling which were defined as follows:

- construction and calibration of model reflecting hydrodynamic state of ground water stream,
- carrying out simulations which would make possible definition of directions and estimation of velocity of groundwater flow in the drilling pad area and, in this way, delineation of an area susceptible to contamination in result of spread of pollutants in ground water.

Taking environmental conditions from the time period between completion of the well and preparations to the fracturing treatments as the background state, field works and laboratory analyses were carried out in the Stage II to document the state of ground water at that time. Ground water samples were collected at 9 selected documentation sites and field measurements were made to determine basic water quality parameters and indicators (electrical conductivity, pH, water temperature, concentrations of chlorides Cl^-, sulfates SO_4^{2-}, nitrates NO_3^{2-}, nitrites $NO_2^{2-}$and ammonia nitrogen NH_4^+). Before sampling all the hydrogeological wells were always developed prior to sampling using pumping action to clear them of stagnant water. This was done using a pump installed in a given well or a mobile one. Samples were taken in accordance with procedures used in studies for the State Monitoring of Environment System in Poland. The range of determinations of parameters and indicators was also the same as accepted in assessments of chemical state of ground water for that institution. Location of hydrogeological objects sampled in the Stage II of the studies is shown on the documentation map (Annex no. 1).

The Stage III was connected with studies carried out during the fracturing treatment on the

Łebień LE-2H well. This was the time of collecting information concerning volumes of water used in the fracturing treatment and analysis of the water circulation system in the course of processes of stimulation of shale gas resources.

The Stage IV was connected with monitoring ground water quality in direct neighborhood of the Łebień well by making measurements and taking water samples from water well situated in the drilling pad area for laboratory analyses (Fig. 17).

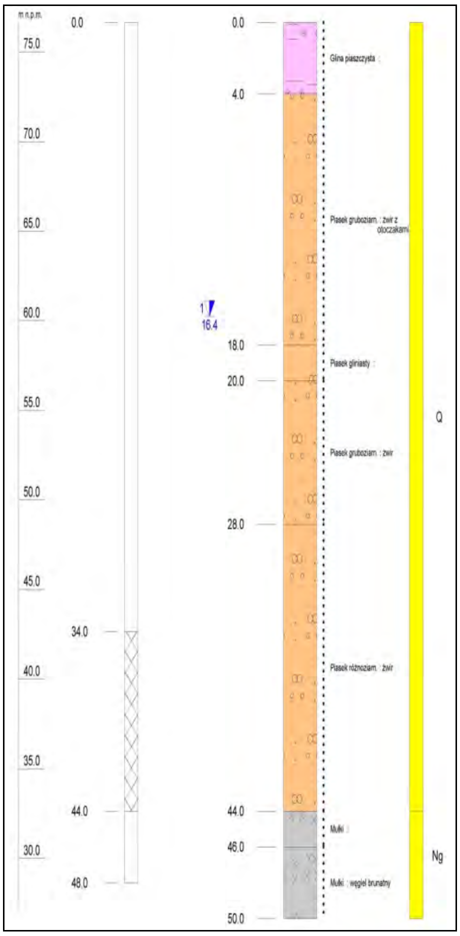

Fig. 17. Column of well situated in Łebień drilling pad area PGI-NRI Central Bank of Hydrogeological Data)

The Stage V began with completion of the last treatments on the well and tight closing of the well head. It was the last stage of studies carried out within the frame of the environmental impact assessment and comprised final analyses. Sampling of technological fluid stored in the basin (and reused in the treatments) was continued for the needs of assessment of water management in the treatment operations. Water samples were once again taken from the water well situated in the drilling pad area and representing key reference point for assessment of the state of ground water in areas directly adjacent to the drilling pad. At the same time, results of chemical analyses of the fracturing fluids were used to differentiate substances usable as markers for evaluation of impact of the hydraulic fracturing treatments on the state of ground water (substances not occurring in the natural environment, proven to be present in technological fluids used in the operations and identifiable in a wide spectrum). Possibilities of migration of potential contaminations were defined on the basis of analysis of hydrogeological conditions and results of modeling. Moreover, points for further studies and observation were indicated and recommendations for further monitoring of the studied area were compiled.

7 Results of the studies

7.1 Seismic events

Seismic studies carried out from 15 July till 30 September did not record any seismic events which could be linked with the hydraulic fracturing operations performed on the Łebień LE-2H well.

The seismic monitoring station situated at the smallest distance from the drilling pad (at a distance of 1) recorded a paraseismic signal generated by equipment used in the operations, mainly by pumps working at the surface. The comparison with the construction norms shows that vibrations generated by equipment in the course of the fracturing operations did not create any risk for human health and buildings in areas adjacent to the drilling site.

Detailed report from seismic monitoring conducted in the Łebień LE-2H well area are enclosed below (Annex no. 10).

7.2 Emissions (gases, noise, radiation)

Gases emitted to the air

The measurements of concentrations of sulfur dioxide, nitrogen oxides,benzene, methane, carbon monoxide and sulfur hydrogen did not give any results which would be higher than treshold values for determinations made with the used device. This means that concentrations of the analysed indicators are lower than those given in Table 4. It also means that concentrations of the majority of these indicators are lower or at the outmost equal to the obligatory reference concentrations (Regulation of the Minister for Environment of 26 January 2010, concerning the reference values for some substances released to the, Journal of the Law 2010 No. 16 item 87), taking into account uncertainty with respect to the order of magnitude which is contained in definition of the reference concentration.

Table 4. Treshold values for determinations made with the use of Draeger CMS analyser in direct measurements of air pollution

Indicator	Concentration	
	ppm	µg/m^3
Sulfur dioxide	0.4	517
Nitrogen dioxide	0.5	646
Benzene	0.2	259
Methane	20.0	25 860
Carbon monoxide	5.0	6 465
Sulfur hydrogen	0.2	259

The passive measurement technique was also used here. This technique allows for measuring much lower concentrations of selected indicators of pollution. The selected selected included sulfur dioxide, nitrogen dioxide and benzene. This method is based on continuous sorption of pollutants from the air in exposition period of 1 month. Samplers were exposed two times: in August – September and October – November 2011. Their location is shown on the documentation map (Annex no. 1; Points of air pollution measurements no. 1 - 7). The results obtained during the first period of exposition appeared two orders of magnitude lower than the reference concentrations (see Table 5).

Table 5. Results of measurements of air pollution indicators by the passive method

Time of exposition August – September 2011		
Indicator	**Mean concentration µg/m^3**	**Reference concentration µg/m^3**
Sulfur dioxide	5.54	200
Nitrogen dioxide	9.61	350
Benzene	0.70	30

Noise

Measurements of noise level were made at three measurement points in order to trace changes due to emission and propagation of noise in the studied area. Table 6 shows averaged results of measurement series in comparison with maximum acceptable noise level in built-up areas.

Table 6. Results of noise level measurements in vicinities of the Łebień drilling pad

No. as in Annex no. 1	Location	Results of measurements dB			Norms* dB
		19.07.2011	19.08.2011	09.09.2011	
1	Drilling pad boundary (at fence of technological area)	38.1	62.9 – 76.0	56.4	nn
2	By the road to Karlikowo Lęborskie village	36.9	68.6	48.3	nn
3	Close to houses of Karlikowo Lęborskie village	36.2	53.9	44.0	55.0

nn – not normalized

* after Regulation of the Minister of Environment of 14 June 2007 on acceptable level of environmental noise (Journal of Law of 2007, No. 120, item 826)

High-power diesel engines appeared to be the major source of noise during the fracturing operations. Temporary rises of *noise level* of *up* to 77.5 dB were recorded at the boundary fence of drilling pad boundary. After taking into account the background values and time of work of engines, the balanced noise level was estimated at up to 76 dB. Along with distance from the sources, the noise level was decreasing down to about 53.8 dB in proximity of village houses, that is values not exceeding permissible levels for daytime hours (56dB).

Analysis of radon concentration in soil gas

The first series of measurements of radon concentrations was conducted before the hydraulic fracturing treatment on the Łebień LE-2H well. *A*rithmetic mean of the recorded concentrations of radon (^{222}Rn) in soils in the studied area was equal 22.3 kBq/m^3, with concentration values ranging from 2 to do 101.5 kBq/m3. In accordance with the radon risk classification of Akerblum (1986) (below 10 kBq/m^3 – low risk, 10-50 kBq/m^3 – normal, over 50 kBq/m^3 – high), 8 of the analysed samples were characterized as low risk, 20 samples – as normal and 1 – as high (Fig. 18).

The highest concentrations of radon were recorded in NW part of the drilling pad, at a distance of about 100 m from the well head. Radon concentrations recorded in close proximity of the well head (at a distance of 5 m) were at the turn of the low and normal radon risk (10.1 kBq/m^3). The measurements taken at the remaining points in and east of the drilling pad site showed low radon risk. Similar results were obtained at points situated in NW and NE corners of the measurement network whereas values for successive measurement points indicated normal radon risk. It may be stated that 72% of the obtained results indicated low radon rick, 24 % – normal and 4% high.

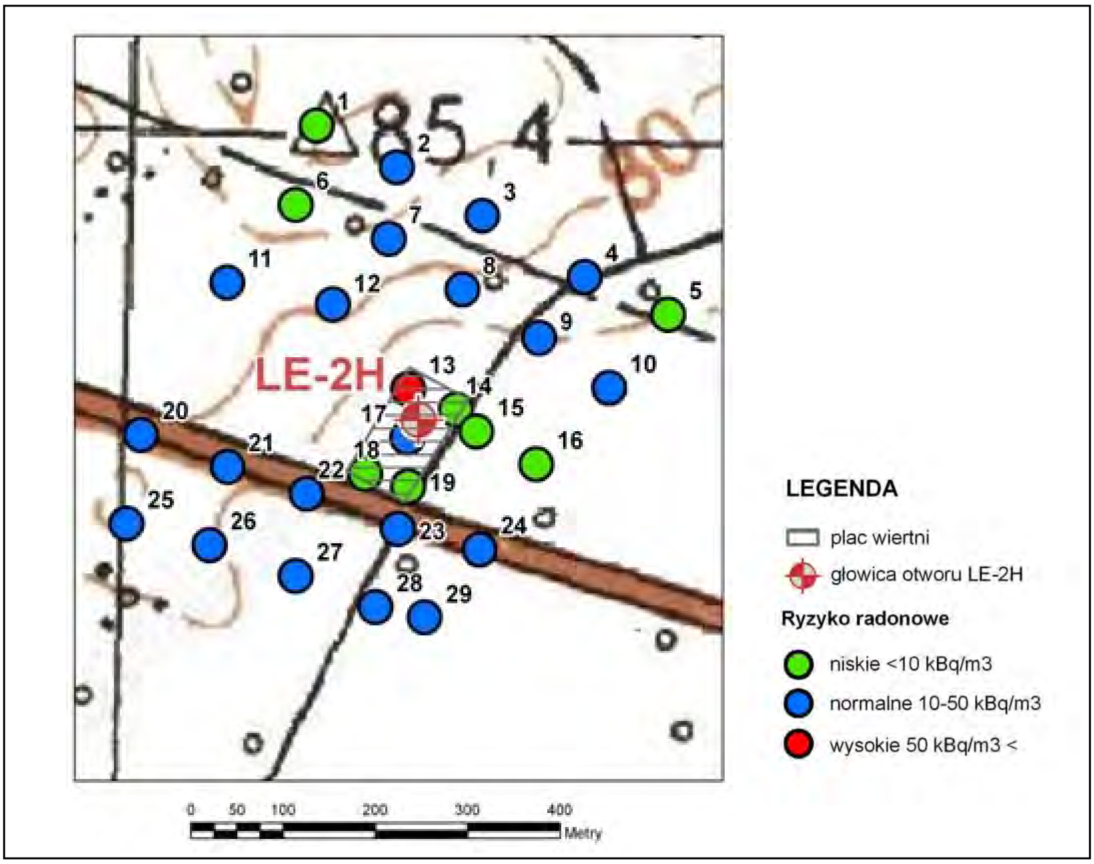

Fig. 18. Results of measurements of radon concentrations in soil gas at the background of topographic map of the studied area.

Arithmetic mean of the second series of measurements of radon (^{222}Rn) concentrations was equal to 8.7 kBq/m^3 whereas the obtained measurement values were ranging from as low as 1.6 kBq/m^3 to 42.4 kBq/m^3 as the maximum. 86% of the obtained results indicated low radon risk and only 14% – normal risk.

High differentiation of values of radon concentration is due to lithological variability and differences in thickness of individual layers. This is especially well visible in the case of tills. This is due to the fact that tills are represented here by both sandy-gravel and strongly clayey varieties. Scandinavian material with increased concentration of uranium predominates in their composition and sandy-gravel intercalations in these tills act as collectors of the emitted radon. It should be added that the land surface had to be evened in the drilling pad area from technical reasons. This made it necessary to fill up lows in that surface (some of which were even up to 1 m in depth) with soil. Soil gas samples taken in soils of that kind resulted in further increase in variability of obtained results of measurements.

Comparison of results of the two series of measurements showed arithmetic mean of radon concentrations in soil gas at the sampling points slightly decreased after the fracturing treatments on the Łebień LE-2H well. The arithmetic mean of measurements of the first series was

20.8 kBq/m^3 and of those of the second series – 8.7 kBq/m^3. Decrease in radon concentrations was found at 6 out of 7 sampled points whereas variability of the recorded values of radon concentrations remained generally similar. The radon risk decreased throughout the studied area.

The above mentioned changes should not be linked with operations carried out at the Łebień LE-2H drilling site. The recorded changes in soil gas could be due to such factors as varying atmospheric conditions (pressure, temperature, air humidity, wind power and others) or changes in shallow groundwater level and the resulting slight differences in depth of sampling.

The studies did no show any increase in concentrations of radon (^{222}Rn) in soil gas sampled close to the Łebień LE-2H well, thus excluding diffusion of radon for example along the well bore casing. In the studied area, radon (^{222}Rn) is generated in near-surface zone of geological substratum. The obtained results appear characteristic for regions with highly differentiated lithology of geological substratum.

7.3 Possible shale gas exhalations

Analysis of methane concentrations in soil gas

The measurements of methane concentration in soil gas from the time before the start of the fracturing treatment on the Łebień LẼ2H well were conducted using methodology which made possible obtaining values qualitative in character, showing orders of magnitude of the concentrations only. The highest values were recorded in organic soils occurring in lows of the land surface (point no. 31 at Tawęcino), a waterlogged area close to a creek (Fig. 19), near a flooding near Rekowo Lęborskie (point no. 36) and peat meadows along the Kisewska Struga creek (point no. 38, Figs. 20 and 21). Methane concentration values obtained for the remaining sampling points appeared to be small. Inconclusive results were obtained for a sampling point situated in the drilling side area only. Measurements repeated at that point in short time intervals gave readings ranging from zero to several hundred ppm. Because of location of that point close to vehicle entrance to the drilling pad and high scattering of readings, the obtained values were treated as unreliable. Subsequent studies carried out by the Oil and Gas Institute did not confirm presence of methane at this place.

Fig. 19. Measurement point of methane concentration no. 31 – Tawęcino Nad Torem

Fig. 20. Measurement points of methane concentration no. 36 and 37 – Rekowo Lęborskie

Fig. 21. Measurement point of methane concentration no. 38 – meadow on Kisewska Struga creek

The studies carried out by the Oil and Gas Institute on 5 – 7 September 2011, that is after completion of the fracturing treatment, confirmed low geochemical background values of methane (markedly below 100 ppm) and presence of biogenic methane in waterlogged and peat soils. Biogenic origin of that gas was additionally confirmed by results of studies on isotopic composition of carbon in soil carbon dioxide, which showed ☐ C^{13} equal about -22 $^{o}/_{\infty}$.

The studies conducted by the Oil and Gas Institute in the Łebień LE-2H well area did not reveal any shows of shale gas migration directly after the fracturing treatments on the well bore.

Detailed report from works conducted by the Oil and Gas Institute is enclosed as Annex no. 11.

7.4 Technological fluids and waste

Technological fluids

The fracturing fluid was prepared by Schlumberger at the Łebień LE-2H drilling pad in the course of the fracturing treatment. Substances used in its production were delivered in original packages or containers with identification tags and certificates of origin of a given product as required by the Polish and international law (Fig. 22).

Fig. 22. Identification tags and cerfificates of origin on package of components for production the fracturing fluid

The flowback fluid from hydraulic fracturing operations was cleaned in filters to remove solid particles and make possible its reuse in further technological processes.

The flowback treatment line was built by the Mi SWACO company. In the first stage of clean up, flowback fluid was passed through a separator of gas and condensate to be subsequently discharged into reservoirs for preliminary sedimentary separation. A vortex pump transported the fluid from the reservoir to vibrating sieve with 4 screens for separation of particles over 100 microns in size. Such sieve makes possible quick processing of large volumes of the fluid (1.8 m^3/min) and removal of the largest of suspended particles. After passing through the sieve, the fluid was directed into a filtration station From the sieve the bags capable to catch suspended particles 100 microns and 50 microns and, when needed, 25 microns in diameter. A two-chamber filtration system with cartridges (Fig. 23) was the next element of the technological line for mechanical purification. At the beginning the fluid were forced to pass through 20 micron but later the 10 micron mesh was used. 104 cartridges were working simultaneously at the same time. The purified fluid was directed from the filtration line to open-air reservoir of technical water.

Fig. 23. Filter installation with cartridges

Water balance of the hydraulic fracturing operations (Table 7) was compiled for the needs of the present study. In the course of all the operations about 21 240.19 m^3 of technological water were injected into the well bore. The largest volume of water was used as the major component of fracturing fluid injected in the course of hydraulic fracturing treatment. The volume of 17 784.69 m^3 of the fracturing fluid consisted of 17 322.6 m^3 of water and 462.09 m^3 of chemicals. Gradual retrieval of fluids from the well bore started with drilling through the plugs isolating individual intervals subjected to fracturing. Reduction of pressure gradient in production tests resulted in further flowback of fluids. The process of drilling through the plugs and production tests gave 2 780.7 m^3 of flowback fluids in total, that is about 15.6 % of all the injected fluids.

Table 7. Water balance of the hydraulic fracturing process performed on the Łebień LE-2H well

Types of works	Volume of technological water injected to well bore	Volume of flowback of technological water during the operations	Volume of flowback fluid from fracturing
	[m^3]		
Preparation of well bore to fracturing treatment	324.0	324.0	-
Fracturing	17 784.69	-	-
Drilling out the plugs	3 131.5	3131.5	805.5
Gas tests	-	-	1 975.2
Total	**21 240.19**	**3455.5**	**2 780.70**

The results of studies on chemistry of samples of technological water (Annex no. 6) made it possible to note that:

- Water from the reservoir no. 2, used in the operations in the well bore, markedly differed from that in the drilled water well in chemistry, especially in a few times higher concentrations of chlorides, sodium and barium as well as organic coal, potassium, iron and some other metals.
- Chemical composition of the flowback fluid appeared highly variable. The highest loads were recorded in first days of production tests, when all the plugs have been drilled through and proper fracturing fluid began to flow back to the surface.

- The volume of flowback fluid began to decrease along with continuation of the production tests. This was accompanied by some decrease in chemical load reaching the reservoir no. 1 as purified fluids discharged into that reservoir were diluted due to mixing with earlier used technical fluids less enriched in chemicals.
- Chemical loads recorded in the reservoir no. 2, to which fluids from the reservoir no. 1 were pumped by the end of the production tests, appeared a few times smaller than in the purified flowback fluid coming from installations and fluids of the latter reservoir.

These findings made it possible to establish or confirm the following facts:

- Not all the water used in fracturing treatment was coming directly from the drilled water well as the technological fluid retrieved in the process of dewatering of drilling mud was stored in the reservoir.
- The flowback fluid (understood as a part of fracturing fluid given back by the well bore during drilling through the plugs isolating individual fractured intervals) reached the surface in very small amounts. The fluid begins to come back to the surface in larger volumes with the end of all the injections to the well bore and is characterized by larger chemical loads than that retrieved in the course of drilling through the plugs and well bore clean-up with the use of technological fluid.
- At first, the efficiency of purification of the flowback fluid was unsatisfactory as filter stations were quickly clogged up and fluids discharged to the reservoir no. 1 poorly purified. The situation was improved with the use of vibrating sieve. The fluids stored in the reservoir no. 1 were subjected to one more purification.
- Not all the water stored in the reservoir no. 2 was used in fracturing operations. Therefore, when fluids from the reservoir no. 1 were subjected to final purification and pumped into the reservoir no. 3, concentrations of the analysed chemical substances markedly decreased in result of dilution.

Toxicological studies also confirmed variability of properties of technological fluids. The sample of hydrochloric acid solution was found to be strongly toxic to higher plants and extremely toxic to the remaining bioindicators. The sample of fracturing fluid was weakly toxic to higher plants, fish and algae and strongly toxic to crustaceans. The sample of flowback fluid retrieved after drilling through the second plug was toxic to all the test organisms and strongly toxic to crustaceans. The sample of flowback fluid retrieved after drilling through the fifth and sixth plug was found to be characterized by smaller range of toxicity units, appearing not toxic to weakly toxic to higher plants and fish and toxic to algae and crustaceans. The sample of flowback fluid taken after the nitrogen treatment was toxic to strongly toxic to all the test organisms and extremely toxic to crustaceans. Somewhat lower values of high toxicity units were obtained in the case of flowback fluid sample taken shortly before securing the well head.

Detailed report from toxicological studies is enclosed below (Annex no. 12).

Waste management

The waste stream originating in the course of works connected with hydraulic fracturing in shale gas exploration comprised two major groups of waste:

- Waste originating in result of drilling and those from fracturing operations, called here as “drilling waste” and “extractive waste”.
- Waste originating during drilling operations and other works at the drilling pad, waste produced by employees and similar one was assigned to the groups no. 13, 15, 16 i 20 (for

example, sorbents, solvent-saturated cloth, oils and lubricants, municipal waste). The waste was generated during all the operations performed at the drilling so it is not possible to state how large was its part generated during the fracturing treatment operations. This waste is beyond the scope of this study but it should be stated that it is managed properly and in accordance with the obtained permits (including selective waste collection and contracts for removal by licensed *waste hauling companies*) (Fig. 24).

Fig. 24. Containers for selective waste collecting at the Łebień well site

In order to get indispensible decisions concerning waste management, Lane Energy Poland Ltd. applied to the Marshal of Pomeranian Voivodeship on 20 February 2011 with request for decision approving program of extractive waste management (in accordance with Art. 9. par. 1 and 3, Art. 11. par. 1 and Art. 40 par. 1 point. 2 of the Act of 10 July 2008 on extractive wastes, the Voivodeship Marshal is the proper organ to make *decision on* issues concerning extractive waste in the case of undertakings for which concessions for prospecting, exploration and exploitation of mineral resources was issued by the proper minister for environmental issues or voivodeship marshal). The company applied for decision which would be valid for two years.

Before issuing the decision, the Marshal of Pomeranian Voivodeship asked:

- Head of the Nowa Wieś Lęborska commune (letter no. DROŚ-S.7240.91.2011 EB of 31 March 2011) and
- Director of the Regional Mining Authority in Poznań (letter no. DROŚ-S.7240.91.2011 EB of 31 March 2011).

for opinion on the above mentioned request of Lane Energy Poland Ltd.

Both organs gave positive opinion for the above mentioned request for decision approving program of extractive waste management:

- decision of Head of the Nowa Wieś Lęborska commune of 6 April 2011 (letter no. RR.6230.2.2011),
- decision of Director of the Regional Mining Authority in Poznań of 18 April 2011 (letter no. 001/521/0022/11/02343/BP).

On 2 May 2011 the Marshal of the Pomeranian Voivodeship has issued decision approving program of management of extractive waste generated at the Łebień LE-2H drilling site for Lane Energy Poland Ltd. (letter no. DROŚ-S.EB.7240.20011.EB).

Moreover, Lane Energy Poland Ltd. applied to the Head of the Lębork District with request for decision approving program of hazardous waste management (in accordance with Art. 17 par. 1 point 1, Art. 19 par. 2 point 3 and 5 and Art. 21 and 63 of the Act of 27 April 2001 on waste). The Head of the Lębork District asked the Head of the Nowa Wieś Lęborska commune for opinion on the above mentioned request and got his positive opinion issued on 6th of April 2011 (letter no. RR.6230.1.2011). On 18 April 2011 the Head of the Lębork issued a decision approving the program of hazardous waste management (letter no. OŚ.II.7644-79/10). This decision was valid till 31 December 2011.

On 21 March 2011 Lane Energy Poland Ltd. submitted to the Head of the Lębork District an information about non-hazardous waste generated during works on prospecting and exploration of hydrocarbon resources in the Łebień LE-2H well.

During works connected with hydraulic fracturing performed on the Łebień LE-2H well there was generated drilling wastes assignable to the group 01[2] subgroup 01 05[3] type 01 05 08[4] according to the Regulation of the Minister of the Environment dated 27 September 2001 on waste catalogue (Journal of Laws No. 112, item 1206). The extractive wastes had solid, semi-liquid and liquid consistency. They were disposed in two ways, in accordance with decisions granted to Lane Energy Poland Ltd.

Solid waste mainly included quartz sand (propant) retrieved from flowback fluids on filters and cartridges of the above discussed system of flowback fluid purification or scattered around the drilling pad during transport or pouring into fracturing fluid producing installations. The waste, in amount of 7.9 Mg was passed to PHU Trade Michał Leśny company, Zawady 12, 63-520 Grabów nad Prosą, having decision of the Head of the Lębork District dated on 14 April 2010 – permit for waste recovery. The waste generated in the course of fracturing process was used in recultivation of a waste disposal facility at Lucino (Wicko commune), performed using proprietary technology of the operator. Extractive waste was transported to Lucino by FHU Mikom company, ul. Chełmińska 24, 64-550 Duszniki, having decision of the Head of the Lębork District dated on 21 June 2010 – permit for waste hauling.

Technology of drilling waste recovery for the purposes of cupping and recultivation of a waste disposal facility, used in recultivation of the facility at Lucino, comprises five steps in its implementation:

- Waste identification – definition of code and analysis of physico-chemical and rheological properties of waste from the point of view of its use and selection of stabilizing-solidifying media. This is the stage of acceptance of waste when suitable for recovery.
- Selection – decision for what purpose a given waste type may be used in recultivation, based on results of quality control.
- Stabilization – solidification – mixing and granulation of waste with cementing media - cement, active fly ash, bentonite, gypsum and others.

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[2] Waste generated in the course of prospecting, extraction and physical and chemical processing of ores and other mineral raw materials

[3] Drilling mud and other drilling waste

[4] Drilling mud yielding chlorides and wastes other than listed in 01 05 05 i 01 05 06

- Adjustment of properties to those of usable material (by densification and fragmentation).
- Monitoring – qualitative-quantitative control of the used waste material.

It appeared not possible to get documents which would confirm that the above mentioned requirements have been matched by waste from the fracturing operations on the Łebień well. The site inspections at the Lucin facility gave only a partial confirmation that some selection was conducted. However, it remains uncertain whether or not this part of material is subjected to any physico-chemical and rheological analyses. The only certain information is that PHU Trade company did not reject the waste from fracturing operations as not matching requirements of the above discussed technology and that the company was actually peforming periodic analyses of mixtures of its own production. An additional inspection of the Lucin waste disposal facility, carried out by the Voivodeship Inspectorate for Environmental Protection on 20 October, 2011, did not find any law violations or faults.

The remaining waste, including more liquid sediments from the open-air reservoir for storage of purified technological fluids, was also assigned the code 01 05 08. The waste, 86.4 Mg in amount, was transported in three conveys of trucks to Spółka z o.o. Port Service, ul. Mjr Sucharskiego 75, 80-601 Gdańsk, having decision of the Pomeranian Voivode dated on 15 July 2005 – integrated permit for running installation of waste recovery and utilization.

The cards confirming delivery do not yield any information on process to be used in utilization and the operator did not apply for any document confirming recovery and recycling of that part of the waste. However, it is known that Port Service company is running the Station of Thermal Treatment of Waste, in which waste is utilized at temperature of 1 100^{o}C and waste heat recovered. This technology secures full utilization of the waste and the installation does *not* generate any *emissions hazardous for the environment* thanks to a system of flue gas purification. Fly ash from waste combustion is analysed and disposed depending on its properties: non-hazardous waste is sent to Konin and those recognized as hazardous - to one of the Member States of European Union.

7.5 Influence on surface water

Water purity state in the Kisewska Struga creek from before the fracturing operations is characterized by results of analysis of a sample taken on 19 July 2011. There are also available archival results of periodic checks of water quality in that creek, made by the Voivodeship Inspectorate for Environmental Protection, Delegature in Słupsk, in the year 2009.

The studies were carried out in a surveyed creek section, close to the place where the Kisewska Struga flows into the Łeba river. This point is situated downstream of potential spread of pollution from the Łebień well site. The obtained results showing good quality of water before the start of fracturing operations are given in Table 8. The enclosed archival data represent average concentrations of pollution indicators in samples taken each month in the year 2009. The presented values appear consistent with those chosen for the needs of analysis of surface water quality, conducted within the frame of studies on environment of the Łebień area.

Table 8. Results of studies of surface water performed before the fracturing operations

No.	Indicator	Sampling in 2009 (average of 12 values)	Sampling on 19.07.2011 r.	Normative values*
1	pH	7.9	8.1	6-8.5
2	Dissolved oxygen (mg/l)	9.73	9.78	>7
3	BOD_5 (mg/l)	4	1.4	<3
4	Chlorides (mg/l)	no	10.9	<200
5	Sulfates (mg/l)	no	36.4	<150
6	Sodium (mg/l)	no	0.592	nn
7	Potassium (mg/l)	no	3.07	nn
8	Sum of nitrite and nitrate nitrogen (mg/l)	1.72	1.58	nn
9	Total Kjeldahl Nitrogen (mg/l)	0.848	0.756	2
10	Total nitrogen (mg/l)	2.57	2.34	<5
11	TOC (mg/l)	9.41	4.27	<10
12	Sum of hydrocarbons C10-C40 (mg/l)	<0.1	<0.1	<0.2
13	Boron (mg/l)	no	<0.010	<2
14	Anionic detergents (mg/l)	no	<0.1	nn
15	Non-ionic detergents (mg/l)	no	<1.0	nn
16	Sulfides (mg/l)	no	0.11	nn

* after: Regulation of Minister of Environment of 20 August 2008 on the method of classification of surface water bodies (Journal of Law 2008 no. 162 item 1008)

no – not determined, nn – no standard
Normative values matched
Normative values exceeded

Table 9. Results of studies of surface waters performed after the fracturing operations

No.	Indicator	Sampling on 30-08-2011	Sampling on 20-09-2011	Normative values*
1	pH	7.7	7.8	6-8.5
2	Dissolved oxygen (mg/l)	10.19	9.87	>7
3	BOD5 (mg/l)	1.1	1.4	<3
4	Chlorides (mg/l)	11.8	11.7	<200
5	Sulfates (mg/l)	36.9	33.7	<150
6	Sodium (mg/l)	5.69	5.67	nn
7	Potassium (mg/l)	1.76	1.86	nn
8	Sum of nitrite and nitrate nitrogen (mg/l)	1.49	1.65	nn
9	Total Kjeldahl nitrogen (mg/l)	1.02	0.825	2
10	Total nitrogen (mg/l)	2.51	2.48	<5
11	TOC (mg/l)	4.49	5.19	<10
12	Sum of hydrocarbons C10-C40 (mg/l)	<0.1	<0.1	<0.2
13	Boron (mg/l)	<0.010	<0.010	<2
14	Anionic detergents (mg/l)	<0.1	<0.1	nn
15	Non-ionic detergents (mg/l)	<1.0	<1.0	nn
16	Sulfides (mg/l)	<0.04	<0.04	nn

* after: Regulation of Minister of Environment of 20 August 2008 on the method of classification of surface water bodies (Journal of Law 2008 no. 162 item 1008)

no - not determined, nn - no standard
Normative values not exceeded
Normative values exceeded

Successive samples were taken after the end of fracturing operation, on 30 August and 20

September 20.09.2011. Table 9 presents comparison of the obtained values with the standards. All the standardized indexes match the obligatory normative values. The comparison showed that all measured concentration of pollution indicators do not exceed threshold values established for the first class of water quality as given in the Regulation of Minister of Environment of 20 August 2008 on the method of classification of surface water bodies' status. The detergents were not found (concentrations below detection limit).

7.6 Impact on groundwater

Numerical model of hydrodynamic conditions in the studied area

A numerical model was built to assess the hydrogeological conditions in the vicinity of the works and to define the possibility of the migration of the potential contaminants. The groundwater flow simulation software Groundwater Vistas 5 was used with the modules MODFLOW, MODPATH and PEST. The ArcGIS 9.1 environment was used for the management of the field works data and archive hydrogeological data. To make the modelling investigations the study area was discretizated, the model boundaries were defined and the boundary conditions were determined. After the hydrogeological structure of the model was determined the appropriate simulation algorithm was selected. This enabled to carry out a series of model calibration runs to determine the effective values of the aquifer permeability. The square 100m by 100m mesh was superimposed over the investigated area making the 70 columns by 56 rows grid. The total area of the model is 39,2 km^2. The coordinate system used is PUWG-1992.

The northern, western, southern and partially eastern boundary of the model was defined as a constant head (1^{st} type) boundary. The southern section of the eastern boundary was defined as a 3^{rd} type boundary along the Kisewska Struga creek. The river head values were determined on the base of the topographic map 1: 10 000 as well as field works. The groundwater recharge and well rates were defined as the 2^{nd} type boundary conditions within the model domain (fig. 25).

It was determined on the base of the investigated hydrogeological conditions that within the study area there is one productive aquifer. The aquifer is confined and locally unconfined built of sands with the gravels of plejstocene age. The discontinuous impermeable layers of small thickness and local extent are present. This implies that the flow model is a one layer structure. The groundwater is recharged by the infiltration of the precipitating water. The groundwater migrates to the south east to Kisewska Struga creek and to the south west to the Łebski canal and Łeba river which are the drainage base. The investigated area is situated on the low order water divide between the Łeba river and its the Kisewska Struga tributary. This hydrogeological scheme was supplemented by the following assumptions:

- aquifer bottom is non permeable,
- flow field is steady-state,
- vertical groundwater flow is neglected,
- aquifer is hydraulically connected to the Kisewska Struga creek.

The applied mathematical model of the steady-state groundwater flow is presented by the following equation:

$$\frac{\partial}{\partial x}(m(x,y)k(x,y)\frac{\partial H(x,y)}{\partial x}) + \frac{\partial}{\partial y}(m(x,y)k(x,y)\frac{\partial H(x,y)}{\partial y}) + Q\inf(x,y) + Qst(x,y) = 0$$

where:

H(x,y) – groundwater table head at the point (x,y) [L]
m(x,y) – aquifer thickness at the point (x,y) [L]

k(x,y) – permeability at the point (x,y) [L/T]
Qinf(x,y) – recharge flux at the point (x,y) $[L^3/T]$
Qst(x,y) – well rate at the point (x,y) $[L^3/T]$

This equation is solved using the finite difference method for the rectangular regular mesh with the constant spatial step.

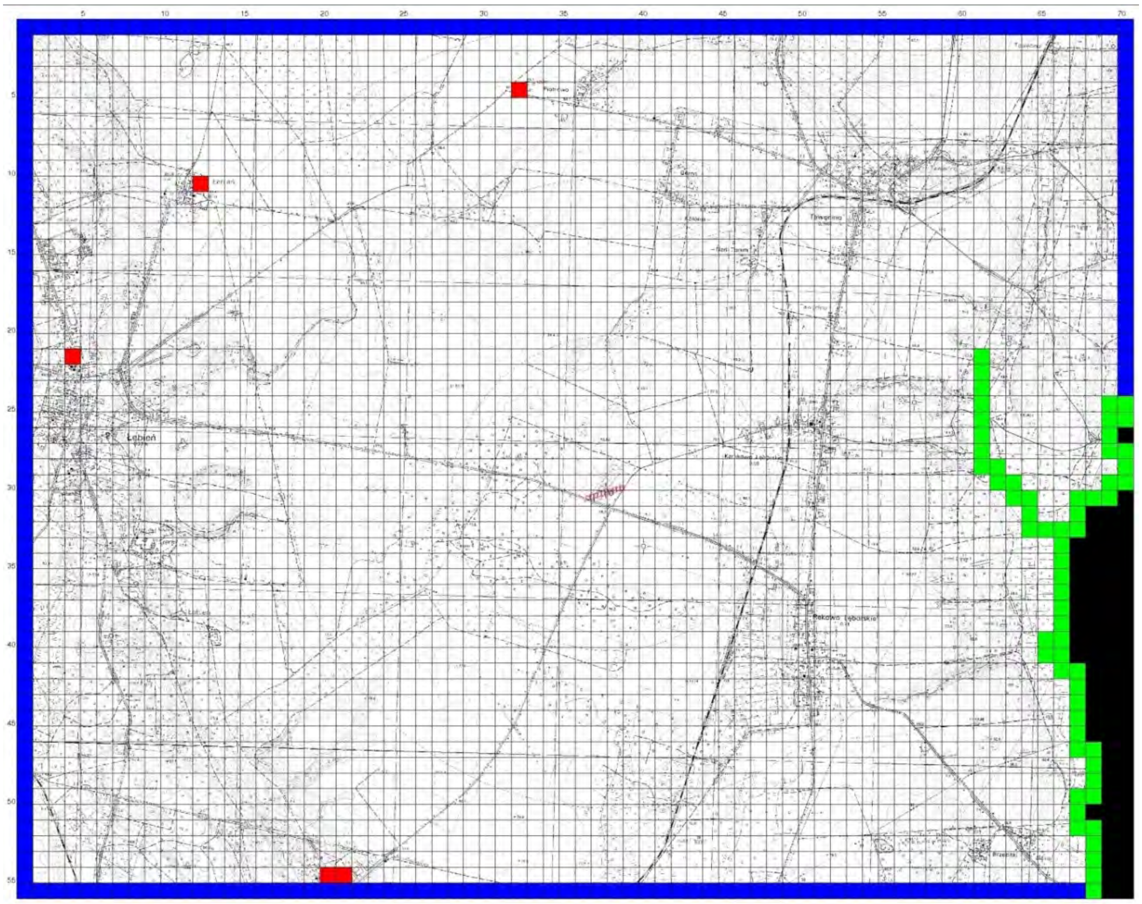

Fig. 25. Boundary conditions: blue – 1^{st} type, red – 2^{nd} type (wells), black - no flow, green – 3^{rd} type (river)

The applied calculation procedure requires to input aquifer top and bottom elevations and permeability values for each node of the finite difference mesh. For the unconfined fragments of the aquifer its top is equivalent to the calculated groundwater table elevation. The aquifer top and bottom elevations were input by the import of the files generated by the ArcGIS 9.1 using the interpolation procedure for the data from the hydrogeological boreholes which reached the top and/or bottom of the aquifer. The interpolation was done using the Inverse Distance Weighting procedure from the Geostatistical Analyst module (fig. 26)

The preliminary distribution of the aquifer permeability values resulted from the interpolation of the “k” values from the pumping tests accessible in the Central Hydrogeological Data Base. This distribution was not confirmed in the model calibration process. This initial distribution was rejected and replaced by the mosaic pattern based on the geomorphological elements. In this approach the model area was divided into 16 subareas with the initially assigned permeability value of 20,0 m/d to each of them. This value was automatically modified for each subarea in the calibration process by the PEST module (fig. 26). The following values for the subareas were obtained (m/d):

I – 4.95	V – 4.28	IX – 38.85	XIII – 31.15
II – 12.95	VI – 6.69	X – 17.59	XIV – 41.49
III – 48.87	VII – 8.90	XI – 10.61	XV – 42.77

IV – 47.35 VIII – 16.00 XII – 8.89 XVI – 60.00

The infiltration recharge was assessed on the base of the long term average precipitation value and surface geology data from the detailed geological map 1: 50 000. Three generalized zones of the recharge were defined (fig. 26).

I – 0.0001 $m^3/24h/m^2$ – for the low permeable surface soils,

II – 0.0003 $m^3/24h/m^2$ – for the medium permeable surface soils,

III – 0.0005 $m^3/24h/m^2$ – for the well permeable surface soils.

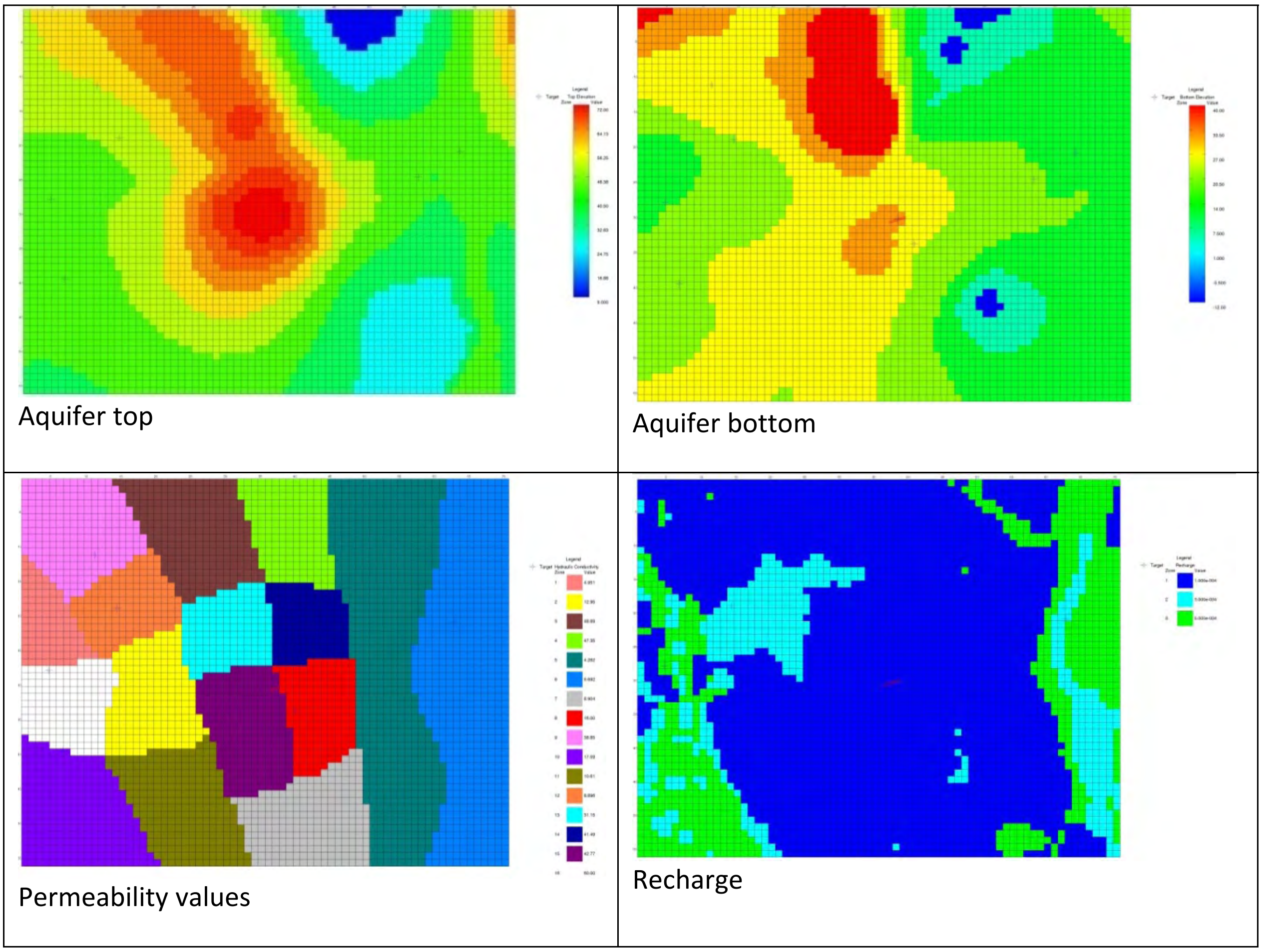

Fig. 26. The model parameters

In table 10 the flow budget for the model domain is presented (m/d).

Table 100. The model flow budget

FLOW IN	FLOW OUT
CONSTANT HEAD = 23253.0293 WELLS = 0.0000 RIVER LEAKAGE = 0.0000 RECHARGE = 7016.0000 TOTAL IN = 30269.0293	CONSTANT HEAD = 22920.7051 WELLS = 232.0000 RIVER LEAKAGE = 7116.2769 RECHARGE = 0.0000 TOTAL OUT = 30268.982

The principle calibration criterion was to minimize the difference between the groundwater table elevations measured in the field and calculated by the groundwater flow simulator. These differences were determined for the 5 observation wells.

During the automated model calibration done by the PEST module the modified hydrogeological parameters values were: the permeability of the aquifer and the river bed conductance. The calibration results are shown in fig. 27.

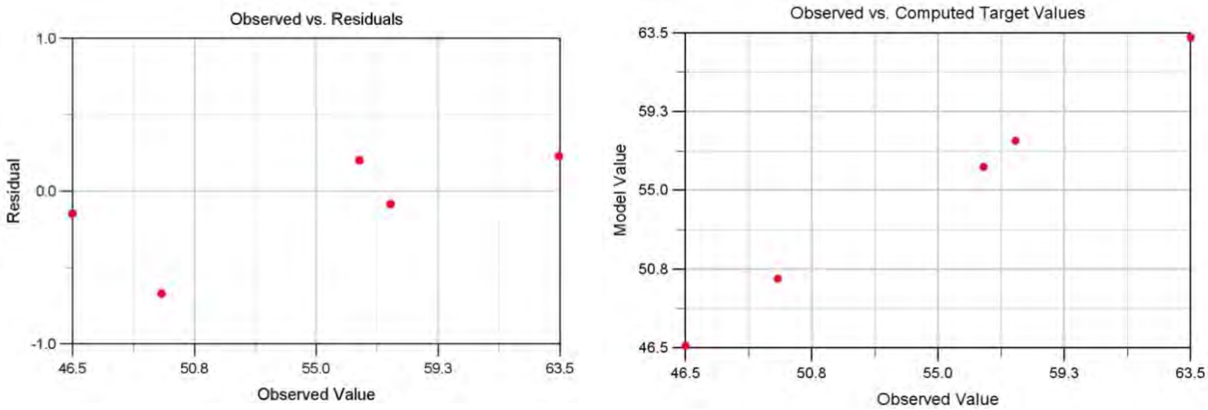

Fig. 27. Automated model calibration results

After each simulation run the analysis of the calculated groundwater heads was done. The calibration process produced the satisfying correspondence between the measured in the field and calculated groundwater heads. In the table 4 the observed and computed heads as well as the residuals are shown. This table also contains the calibration statistics.

Table 11. The calibration summary

Name	X	Y	Observed	Computed	Residual
Łebień ZOZ	417292.83	753633.12	46.5	46.647221	-0.147221
WiertniaLE-2H	420592.12	753397.03	57.6	57.685799	-0.085799
Karlikowo kol.	422525.52	753958.95	49.6	50.268693	-0.668693
Łebień PGR	417950.61	755301.80	63.5	63.270818	0.229182
Rolland rzepak	420827.48	753044.17	56.5	56.296526	0.203474
Residual Mean: -0.093811			Min. Residual: -0.668693		
Res. Std. Dev: 0.324379			Max. Residual: 0.229182		
Sum of Squares: 0.570111			Range in Target Values: 17.000000		
Abs. Res. Mean: 0.266874			Std. Dev./Range: 0.019081		

The mathematical model always constitutes the simplification of the real hydrogeological conditions. This is why model simulation results include certain error which results from the never full knowledge of the investigated hydrogeological system and necessary simplifications made during the construction of the model. In case of the model made to assess directions and flow travel times there are factors limiting the accuracy of the model forecasts as well as acting in favour of the results reliability.

Factors limiting the model reliability:

- small number of observation wells with the possibility to measure water level in the investigated area,
- the investigated area is situated in the groundwater divide zone what makes difficult to precisely determine the flow directions and interpret groundwater contours,
- mosaic distribution of the permeability values.

Factors in favour of the model reliability:

- geological conditions simple and easy to identify,
- known hydrogeological conditions at the site (two drilled water wells),

- model construction and calibration on the base of the reliable geological data from the Central Hydrogeological Data Base and up-to-date field data.

Taking into account the above mentioned factors limiting the model reliability as well as those in favour of this the presented model can be considered as the enough reliable one to be used to determine groundwater flow directions and access flow velocity in the vicinity of the Łebień LE-2H drilling pad. Despite its above mentioned limitations the groundwater flow model is much better forecast tool than analytical calculations methods. This model's reliability will significantly be improved after incorporating into it the results of the proposed monitoring observations.

To calculate and visualize groundwater flow paths and access travel times in the aquifer a MODPATH module from the Groundwater Vistas modelling environment was used.

To solve the travel times problem the groundwater flow was simulated in the vicinity of the borehole site. The hypothetical contaminant particles were placed at the Łebień LE-2H pad. These particles travel distances were calculated in the 10 year time interval with the assumption that the aquifer effective porosity equals to 0.2 (fig. 28).

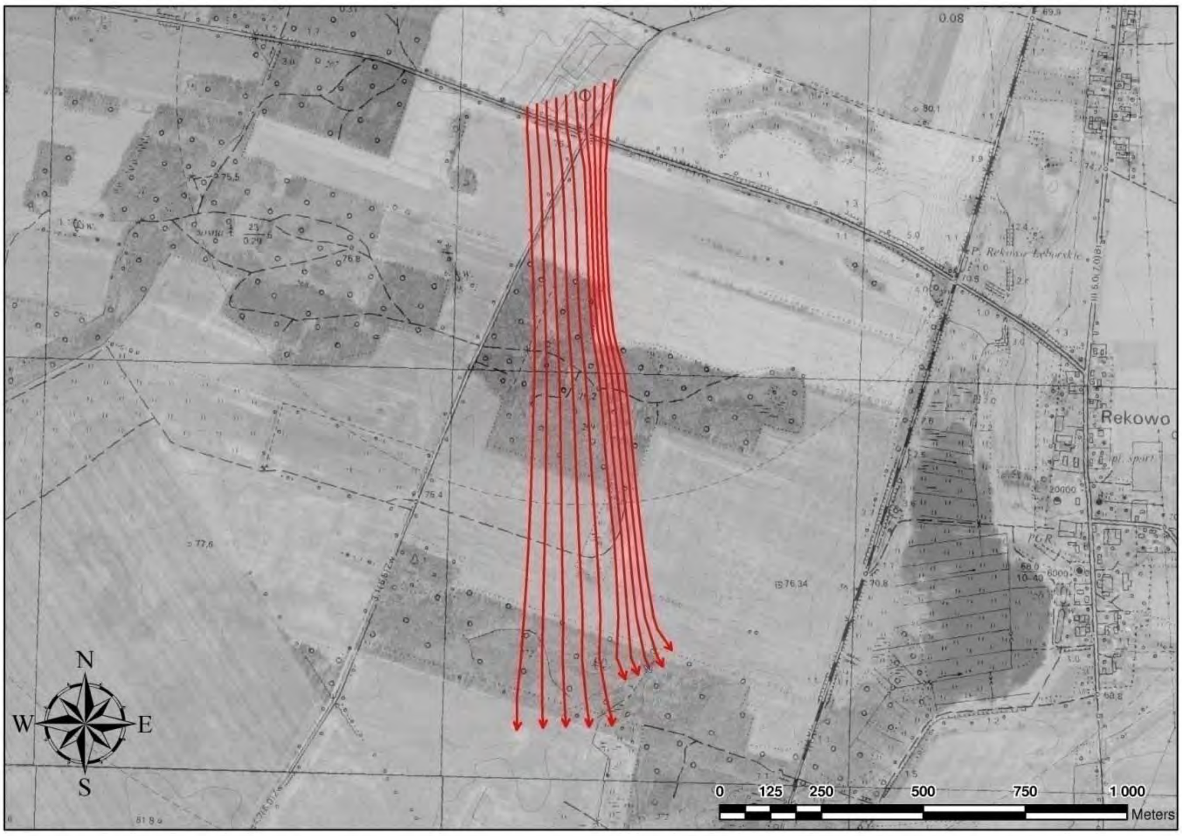

Fig. 28: Travel distances for the 10 year time interval

The results of the above analysis show that the groundwater migrates southward. It cannot be excluded that this migration is to the south south-east (travel paths deviate a little towards Kisewska Struga creek).

The carried out simulation show that in the 10 year time the groundwater migration distance will not exceed 1500 m to the south. The regional groundwater contours pattern shows that this aquifer is drained by Kisewska Struga creek and groundwater travel time from the Łebień LE-2H pad to this drainage base exceeds significantly 30 year period of time.

Prior-to-fracturing state of groundwater in the Łebień well pad region

In July 2011, samples of groundwater were taken at 9 selected documentation points for laboratory analyses performed for defining chemical state of that water before the start of hydraulic fracturing The points selected for sampling operations represented by 8 drilled water wells and one hand-dug one, localized within 8 km radius from the Łebień drilling pad. All these wells are currently exploited. The drilled wells get water from the first aquifer which is the major usable water-bearing horizon in this region. In turn, hand-dug wells get perched water. The sampled points were located concentrically in relation to the drilling pad area, with a special attention paid to the direction to the south and south-east, that is the direction of flow of water from the drilling pad area (Annex no. 2). The selected points are representative for defining actual natural state of groundwater chemistry in the studied area. Table 12 shows values of d basic physio-chemical parameters determined at these sampled points.

Table 11: Basic physio-*chemical parameters determined at sampling points (numbering as in Annex no. 1)*

No. of point	Type of point	User of well	Location	Temperature of water [☐C]	pH	Electrical Conductivity [µS/cm]	Total alkalinity [mgCaCO$_3$/l]	TOC [mg/l]
2	Hand-dug well	Private owner	Rekowo Lęborskie	11.1	6.87	377	160	3.5
4	Drilled well	Communal intake	Tawęcino	9.0	7.84	318	101	<1.0
7	Drilled well	Communal intake	Łebień	10.2	7.48	474	194	<1.0
9	Drilled well	Private owner	Karlikowo Lęborskie 4	10.2	7.26	772	279	1.9
10	Drilled well	Private owner	Karlikowo Lęborskie	9.6	7.89	309	99	<1.0
11	Drilled well	Łebień LE-3H well operator	Łebień	9.4	7.74	314	116	<1.0
13	Drilled well	„Rolland"	Obliwice	-	8.43	130	118	1.4
15	Drilled well	„Rolland"	Obliwice	9.5	7.78	362	125	<1.0
17	Drilled well	Communal intake	Obliwice	10.3	7.57	324	123	<1.0

Values of basic physio-chemical parameters determined in the studied water samples fall within the range of hydrogeochemical background (range of characteristic concentrations consistent with that given in the Regulation of Minister of Environment of 23 July 2008 on criteria and methods of classification of groundwater status assessment), what qualifies the water as of a good chemical state.

The studied water is characterized mainly by low specific electrolytic conductivity and neutral to weakly alkaline reaction what is typical of water of infiltration origin in temperate climate. Total organic carbon content (TOC) is low and falls within the range of values admissible for the water quality class I (<5 mg/l).

47 organic and 49 inorganic indicators were determined in order to make the chemical

characteristic of the studied groundwater samples complete. Table 13 shows the results of these determinations (numbering as given in Table 12).

Table 13: Results of determinations of selected inorganic elements* (green – Class I, yellow – Class II, orange – Class III, brown – Class IV, red – Class V)

No. of point		*10*	*2*	*9*	*15*	*11*	*17*	*7*	*4*	*13*
HCO_3	mg/l	121	195	340	153	142	150	237	123	144
NO_2		0.02	0.07	< 0.01	< 0.01	< 0.01	< 0.01	0.01	< 0.01	<0.01
NO_3		17.7	20.2	103	0.21	9.52	0.01	3.00	28.9	<0.10
NH_4		<0.05	0.10	<0.05	0.22	<0.05	<0.05	0.10	<0.05	<0.05
Cl		8.32	4.93	21.4	17.8	11.4	11.9	19.8	13.1	18.2
SO_4		50.1	10.6	50.6	56.3	40.8	47.1	56.7	37.4	6.72
Ca		54.7	21.8	128.1	67.8	57.3	59.7	89.8	53.4	12.6
Fe		0.01	0.01	<0.01	2.30	0.12	0.98	0.25	0.01	0.07
K		1.4	87.2	41.2	1.2	0.9	1.3	2.0	0.8	0.7
Mg		5.0	3.8	10.9	6.2	4.9	6.0	8.1	6.4	3.0
Mn		0.014	0.017	<0.001	0.144	0.014	0.084	0.116	0.011	0.032
Na		6.1	4.6	11.0	5.9	6.3	4.7	8.7	6.2	6.3
P		0.06	1.74	<0.05	0.06	<0.05	<0.05	<0.05	<0.05	<0.05

* Classification of quality classes as in Annex to the Regulation of Minister of Environment of 23 July 2008.

In summing up it should be stated that groundwater of the water-bearing horizon widely exploited throughout the Łebień well area are characterized by generally good chemistry. The obtained values of concentrations of individual indicators fall in the range of those groundwater quality classes I and II or III, indicating good state of groundwater chemistry (as given in the Regulation of Minister of Environment of 23 July 2008 on criteria and methods of classification of groundwater status assessment). Only in the case of water samples from the points no. 2 (Rekowo Lęborskie – hand-dug well) and 9 (Karlikowo – private drilled well) the analyses showed deteriorated water quality. Concentrations of potassium recorded at these points exceed boundary values for good state of water. Moreover, high concentration of nitrates recorded at the point no. 9 indicates *a*gricultural contamination of groundwater in direct vicinity of this documentation point.

State of groundwater in the course of fracturing operations and production tests

Chemical state of water drawn from the water well situated in the Łebień LE-2H drilling pad was steadily monitored for the purposes of assessment of potential impact of operations carried out on that well on groundwater. Taking into account hydrogeological conditions in the direct proximity of the well head and the drilling pad area, the water well only 67 m distant from the well head was recognized as the most representative for assessments of changes induced in groundwater chemistry by the operations.

The benchmark water well was sampled for laboratory analyses five times in the course of the operations Table 14 shows results of these analyses. The studies and samplings were carried out in the course of the following operations performed on the Łebień LE-2H well:

1. after completion of the well, in the course of preparations to the fracturing treatment;
2. after injection of fracturing fluids, Turing drilling through the plugs;
3. in the course of gas tests (during injection of nitrogen);
4. after the end of gas tests and well head securing;
5. after the end of all works at the drilling pad.

The obtained results of analyses show that chemistry of the studied water remained unchanged. Concentrations of the analysed indicators did not increase which shows that there was no influence of the performed operations on quality of groundwater in the the Łebień well area.

The results of studies on the water well from the drilling pad were the reason of decision to give one more round of sampling the village water wells studied during the first stage of works. Moreover, the results of modeling provided data on direction and time of flow of the groundwater. The data gave the basis for compilation of recommendations for further monitoring of the Łebień LE-2H well pad region.

Table 14: Results of measurements made on water samples from water well located in the drilling pad area, taken at different stages of works (numbering explained in the text)

Sampling stages		1	2	3	4	5
Indicator	No. of sample / Unit	5	24	28	29	32
pH	-	7.74	7.71	7.70	7.71	7.73
PEW	mS/cm	314	374	358	360	350
TOC	mg/l	<1.0	<1.0	1.4	<1.0	1.1
Total alkalinity	mg $CaCO_3$/l	116	126	121	125	129
HCO_3	mg/l	142	154	148	153	157
NO_2		<0.01	<0.01	<0.01	<0.01	0.02
NO_3		9.52	9.18	9.29	9.99	7.54
NH_4		<0.05	<0.05	<0.05	0.16	<0.05
Cl		11.4	14.8	11.8	10.4	10.3
SO_4		40.8	40.8	41.9	45.2	41.4
Ca		57.3	59.9	60.6	57.6	58.0
Fe		0.12	0.11	0.08	0.02	0.06
K		0.9	4.9	4.9	0.8	0.9
Mg		4.9	5.2	5.3	5.1	5.0
Mn		0.014	0.015	0.015	0.009	0.013
Na		6.3	6.4	6.4	6.4	6.3
P		<0.05	<0.05	<0.05	<0.05	<0.05

8 Summary of environmental impact of hydraulic fracturing till the end of works

Air

The works carried out at large depths in order to make rocks of gas-bearing formations more permeable do not did not generate any air pollution. The released gas was neutralized at well flare stack by oxidation of hydrocarbons and accompanying gases.

Diesel engines used to run the fracturing operations were found to be an effective source of air pollution. Temporary emission of exhaust gases makes strong impression when assessed visually. However, measurements taken in windward, potential stream of exhaust gas showed that permissible levels were not exceeded. Moreover, environmental effects of such emission are diminished additionally by very limited time of work of these engines.

Noise

Work of high-power diesel engines was the major source of noise during the fracturing treatment. Temporary increases in noise levels as measured at the fencing on the well site were equal 77.5 dB. Taking into account the background values and time of work of engines, the balanced noise level was estimated at 76 dB. Along with distance from the sources, the noise level was decreasing down to about 53.8 dB in proximity of village houses, that is to the values not exceeding permissible levels for daytime hours (56dB).

Soil gas

Up to now the hydraulic fracturing treatment performed on the Łebień LE-2H well did not generate any noticeable changes in composition of soil gas, especially in concentration of radon and quantities and composition of methane. Methane was also not found in aeration zone of water intake in the drilling pad area. It follows that the treatment did not open routes for migration of gases from deep-seated horizons in the drilling pad area and even in direct proximity of the drilling rig.

However, it is not excluded that such migration may take place in the future, for example when the Łebień LE-2H is used in a new phase of exploration of shale gas resources or it is closed due to leaks. However, the latter risk is common for all wells of so large depth, not only those made within the frame of prospecting and exploration of shale gas resources.

Land surface

The Łebień LE-2H well site has become an element of landscape of the Nowa Wieś Lęborska commune several months ago. Its appearance has been changing in dependence of operations performed in a given time but in opinion of the local community the well was not blemishing the beauty of the landscape in any significant way. The flame rising over flare stack turned to be some kind of attraction not only tourists as the well site started to be visited by representatives of various institutions, media and even ordinary citizens.

At present the well site is set in order and all the unnecessary equipment such as well derrick and mobile reservoirs removed. Well heads of the two wells are secured and under protection for 24 hours (Fig. 29).

Fig. 29. Secured well head of the Łebień LE-2H well (October 2011)

Impact of the hydraulic fracturing performed on the Łebień LE-2H well on the land surface was short-lasting and did not result in any visible changes. It was mainly related to load of the whole drilling equipment and materials brought to the well site. Total cumulative effect of the operations on land surface in the drilling pad area, including physical changes and eventual pollution, will be more visible and accessible when concrete paver blocks forming pavement surface of the drilling pad are removed.

The hydraulic fracturing treatment did not result in any ground vibrations or shaking which could create risk of damage for buildings or infrastructure.

The hydraulic fracturing treatments resulted in origin of small amount of solid waste which were disposed at the recultivated communal waste disposal facility. In large part the solid waste consisted of quartz sand which was spilled around the site during delivery and therefore not used in the treatments

Used fracturing fluids that returned to the surface were found to be changeable in properties but generally characterized by significant content of chemicals and high toxicity to various groups of organisms. It should be stressed that these flowback fluids were under constant control which precluded any leaks to the environment under normal operating conditions. Thanks to the use of a special purification line and continuous monitoring of its efficiency it became possible to clean up the flowback fluids to such degree that their large part was reused as technological fluids in fracturing operations on other well. in y could be reused achieve such level of purification This resulted in reduction of amount of liquid waste. The liquid waste was finally sent for utilization by licensed specialized operator and, in this way, chemical loads of that waste did not get into the environment.

Surface water

The studies hitherto carried out did not show any influence of the works connected with the hydraulic fracturing on quality of surface water. The works at the Łebień well site have been organized and conducted with such care that there were no discharges of pollutant to a neighboring creek studied by the Voivodeship Inspectorate for Environmental Protection in Gdańsk. There were no allegations or complaints concerning illegal dumping of waste in the environment. The drilling works at large depths had no effect on hydrogeological conditions in the vicinities of the well pad area. Therefore, in connection with at least temporary closing of operations at the Łebień well site, it would be difficult to expect any effects of previous operations on quality of surface water.

Groundwater

Water needed for technical purposes was drawn for months from local Quaternary water-bearing horizon and stored in open-air reservoirs at the well site. Therefore, despite of use of large volumes (almost 18 000 m^3) of water in the fracturing operations, the groundwater resources did not diminish in the well area. The water was drawn in quantities consistent with the water rights permit from the intake situated at the Łebień drilling pad.

Taking into account results of studies carried out in the region of the Łebień LE-2H exploratory well till the second half of October 2011 and specific character of the hydraulic fracturing operations performed in August 2011, it should be stated that concluded that all the available data does not confirm any negative influence of these operations on groundwater of that region. Control studies of groundwater in water well situated in the drilling pad area, that is located at the smallest distance from the well head, did not show any deterioration of quality. All the operations carried out at the drilling pad were conducted with care and in the way minimizing risk of negative impact on groundwater. This includes the use of a special system for purification of flowback fluids, storage of waste in leak-proof containers and protection of land surface with concrete paver blocks and liners made of plastic film. It is worth to note that that during the hydraulic fracturing operations there were no accidents nor unforeseeable events which would create risk for groundwater. However, it should be stated that the hydrogeological conditions prevailing in this region make it advisable to recommend conducting control determinations of selected physico-chemical indicators at sampling points localized at the direction of flow of groundwater.

Human factor

The talks with inhabitants of villages situated close to the Łebień well site showed that they are aware of nuisances and problems connected with shale gas exploration, especially from drilling and other operations. However they turned to be supporters of exploration and extraction of that raw material. Their main arguments in favor for shale gas and explaining their attitude to these issues included: expected financial benefits in the form of exploitation fees, communal investments which would be made possible thanks to these fees, support for economic growth in the commune, new job opportunities, and belief in compensations to be paid for eventual damages or losses. A large part of inhabitants saw the issues in a wider context stating that the country needs that valuable raw material so they will not block its exploitation.

Such attitude is largely due to cooperation of Lane Energy Poland Ltd. with local authorities and community. Within the frame of that cooperation the company has been conducting official consultations with both local citizens and decision-makers of the communal and district and voivodeship level. Such consultations preceded each stage of the works. An information meeting on horizontal drilling and hydraulic fracturing took place in Łebień on April 20, 2011. The meeting was attended by about 50 people including the Head of the Nowa Wieś Lęborska commune, representatives of the Nowa Wieś Lęborska commune office, District Office in Lębork, Pomeranian Voivodeship Marshal's Office, staff of PR firms, journalists and inhabitants of areas situated in the vicinity of the well site. A representative of the Board of Lane Energy Poland Ltd. gave the audience a briefing on questions connected with technical-logistical side of works performed so far and the scope and range of those connected with drilling horizontal section of the well and hydraulic fracturing. The presentation was followed by a discussion concerning the planned operations. The local citizens were mainly afraid of such issues as potential pollution of drinking water with methane, destruction of roads by heavy vehicles, noise levels of the resulting nuisances, potential seismic quakes and drilling accidents. All the questions were answered. One of conclusions from that meeting is that the attitude of citizens of the commune and representatives of the commune and district and voivodeship to the planned operations was very positive. They saw a great potential for further development of the whole region.

Extraordinary environmental hazards (serious accidents and natural catastrophes)

The fracturing operations were performed without any accidents or extraordinary events that would take place in the drilling pad area and create risk for the environment and human life and health.

During the works there were also not noted any severe weather phenomena which could disturb the ongoing operations and create risk for human safety.

9 Recommendations for further studies and observations

Noise

Noise is emitted at all stages of exploration and investments aimed at commercial production of shale gas. It is recommended to monitor noise emissions at the next stages of operation of the Łebień well site. The noise level should be measured close to housing units to make the results of noise measurements usable in long-term policies in noise protection.

Land surface

The Łebień well pad was operating for a long time before the start of the fracturing treatments. This made it impossible to determine natural degree of soil compaction in the drilling pad area. It was also not possible to determine the present state of soil as surface of the whole area of the drilling site is still covered with concrete paver blocks. These were also the reasons why soils of the drilling pad area were not covered by geochemical studies which would make it possible to check whether or not the area became polluted at any stage of the drilling operations. Such studies should be carried out in the case of final shut-down of the mining enterprise, before restoration of the area to its original agricultural use. Because of the lack of determinations of so-called zero state, analogous studies should be carried out in a part of adjacent areas which was not affected by direct influence of the mining authority and the obtained results accepted as the reference level for individual parameters.

If any pollution is identified in area of a mining enterprise after its shut-down, the operator of that enterprise or his successor will be held responsible for removal of any resulting environmental damage.

Surface water

Water quality in the Kisewska Struga is monitored at the measurement point which was also used in in the present study for regional analysis. It is recommended to continue this monitoring by the Voivodeship Inspectorate for Environmental Protection not only for checking potential effects of operations of the Łebień mining enterprise but mainly for gathering database for the purposes of control of the state of environment during eventual shale gas production, if it takes place in this area in the future.

Groundwater

The results of analysis of hydrogeological conditions, especially results of modeling show that seems justified to monitor the area of the Łebień LE-2H exploratory well. Monitoring should cover the water well in the drilling pad area and observation points localized at the direction of groundwater flow.

It is recommended to install three piezoments at the direction of low, below the drilling pad, and one above the pad (Fig. 30). The observation piezometers should be installed at a distance corresponding to one year travel time in the water-bearing layer. Along with water wells localized in the drilling pad area and screened in the bottom part of the water-bearing layer, the piezometers will monitor effects of a potential pollution of groundwater from the surface or the zone adjacent to the well head zone. The piezometers should be constructed in such a way that the observation will cover the whole width of groundwater stream flowing beneath the drilling pad area. The piezometers should screen top part of the water-bearing zone and a part of the unsaturated zone above the interval of water table oscillations, in order to make possible observations of the lightest fraction of oil products.

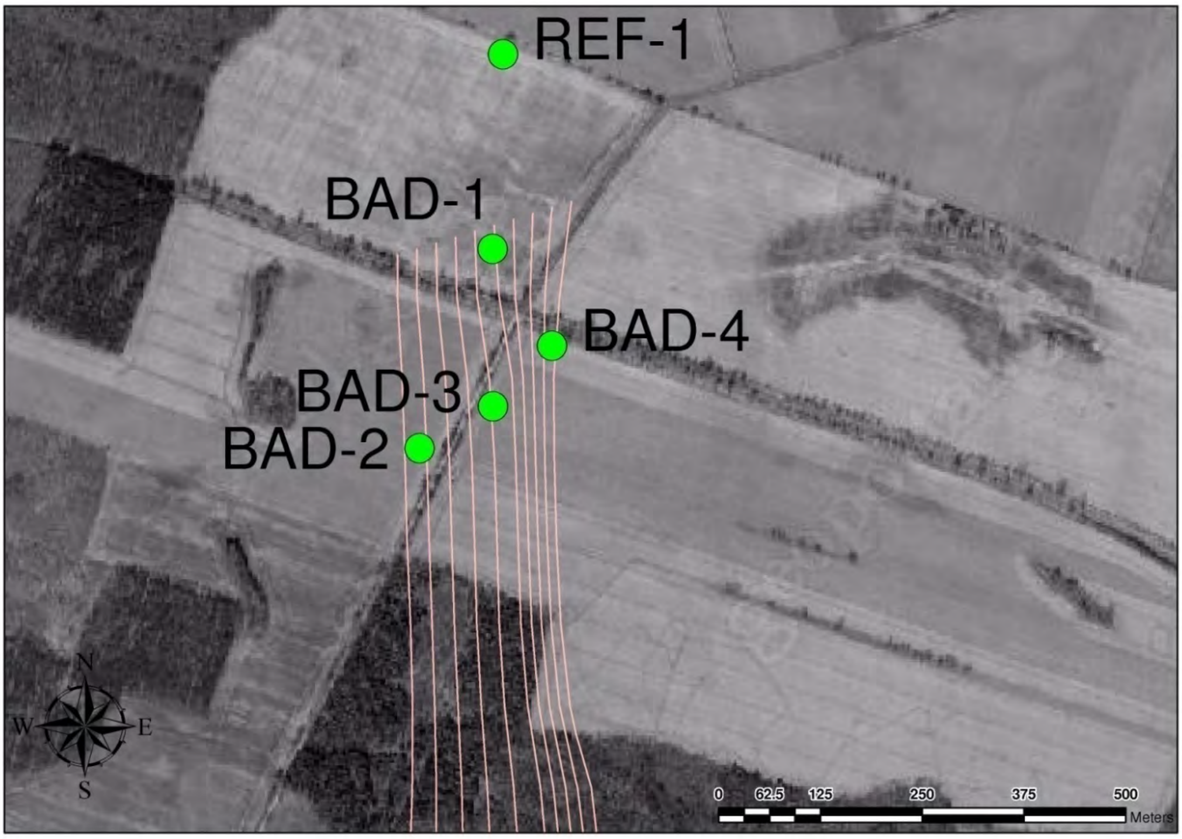

Fig.30. Proposed distribution of observation points

Because of quite significant delay between eventual occurrence of pollution at the land surface and potential contamination of groundwater, it is recommended to install at least one observation well in the drilling which would monitor top and zone of fluctuations of water table.

The passing time through aeration zone was calculated using Bindeman equation:

$$V_a = \frac{1}{n_0}\sqrt[3]{\omega^2 k}$$

where:

V_a - velocity of seeping of water through the zone of aeration

n_o - effective porosity coefficient

ω - infiltration rate

k - Darcy coefficient

The time of percolation will be equal to:

$$t = \frac{l}{V_a}$$

where:

l - percolation distance

Time of water percolation through aeration zone is calculated for two zones;

- Sandy tills forming top of the zone of aeration

$k = 10^{-6}$ m/h = ~ 0,09 m/d	Average value for aeration zone, taken on the basis of lithological description of sections
no = 0,45	Taken from B. Kozerski nomogram (for so low value of filtration coefficient this value should be treated as greatly approximated
l = 3,0 m.	Average value, in drilling pad region

- Coarse-grained sands with pebbles

$k = 10^{-3}$ m/h = ~ 90 m/d	Average value for aeration zone, taken on the basis of lithological description of sections
no = 0,3	Taken from literature
l = 12,0 m.	Average value, in drilling pad region

In both cases the accepted value of infiltration rate was □ = 1,80 10^{-4} m/d (mean value in model domain).

After calculations we obtain time of percolation from the land surface:

t = 945 + 252 = 1197 days = 3.3 years

The above calculations show that observation and studies on water in piezometers and water wells localized in the drilling pad area should last 4 years. When changes in groundwater chemistry are not found during that time, the observations should be phased out. In the case of finding chemistry changes which could be related to pollution from works conducted at the well site it will be necessary to compile a program of studies for the next 4 years, including installation of piezometers at 2-5 years time of flow. It should be also necessary to renew the observation if works at the well site are recommenced anytime after the 4-year observation period.

10 Summary and general conclusions

The studies carried out in the Łebień well area by the research team from June till October 2011 and the complex analysis of the hydraulic fracturing operations performed on the Łebien LE-2H well made it possible to draw the following general conclusions which mainly refer to the procedural-administrative aspects of this process. In presenting general conclusion about limited environmental impact of treatments performed on that well it would be worth to emphasize a few issues related to the treatments, which may be important for analogous works carried out on other wells.

1. As it was shown by Lane Energy Poland Ltd., for cooperation with local community and obtaining acceptance for the planned activities it is necessary to open dialogue with local authorities and society and, first of all, to provide reliable information on the scope and risks connected with these activities, not to say about future benefits. The local society has to get clear message that it is treated as a real partner and the future of its region and, in a wide perspective, the whole country depends on its conscious decisions.
2. The hydraulic fracturing as a stimulating treatment which opens access to shale gas reserves does not bear any long-standing influence on the environment, providing that it is appropriately performed, in accordance with the best professional knowledge and all the legal regulations and norms and those of safety and hygiene of work and adhering to correctly and properly issued administrative decisions.
3. Short-lasting influence of hydraulic fracturing processes on local environmental conditions is mainly connected with increased noise level, heavy traffic of vehicles, including large and heavy ones, and possibilities of origin of a specific waste from technological fluids returning to the surface. The influence may be minimized by the use of appropriate procedures and issuing adequate administrative decisions.
4. By any means the liquid used for the fracturing should be reused in subsequent technological processes after undergoing the appropriate treatment. This liquid should only be used at the site or transported to other places. This will protect the natural environment from the impact of big loads of contaminants during every single fracturing as well as decrease the demand for fresh water to be used in the subsequent operations.
5. Administrative procedures should be updated to allow environmentally safe reuse of flowback fluids as technological fluids in successive hydraulic fracturing treatments also on other wells. This should made it possible to reduce costs of exploration and exploitation of unconventional gas resources and, in this way, future market price of gas.
6. It is necessary to elaborate the methodology of the waste analysis, including the range of studies making possible the differentiation of the types of waste generated during the fracturing process. These waste types are now classified under the common code 01 05 08. Such elaboration would answer the question whether or not

it is necessary to supplement the waste catalogue with additional waste types from the 01 group.

7. Waste generated by hydraulic fracturing should be examined for its physical and chemical characteristics and the obtained results made available for the public. The lack of knowledge of the actual waste properties creates the danger of their inappropriate handling and management by the operators of disposal and remediation facilities.
8. It is highly urgent to elaborate guidelines which would make the management procedures for solid and liquid waste generated during fracturing operations in comply with the legal regulations as well as harmless to the environment.
9. It is highly urgent to continue collecting information on composition of the fracturing fluids to enable carrying out analyses aimed at identification of substances usable as markers in case of migration of contaminants.
10. The experience gained from the hitherto performed studies show the necessity to continue these monitoring studies in other sites where the shale gas prospection and searching works are conducted. These monitoring studies make it possible to assess impact of the fracturing operations on individual components of the environment in a given environmental, geological and hydrogeological conditions.

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Baza danych GIS Mapy hydrogeologicznej Polski 1:50 000 „Pierwszy poziom wodonośny – występowanie i hydrodynamika", Państwowy Instytut Geologiczny – Państwowy Instytut Badawczy, Warszawa

12 List of annexes

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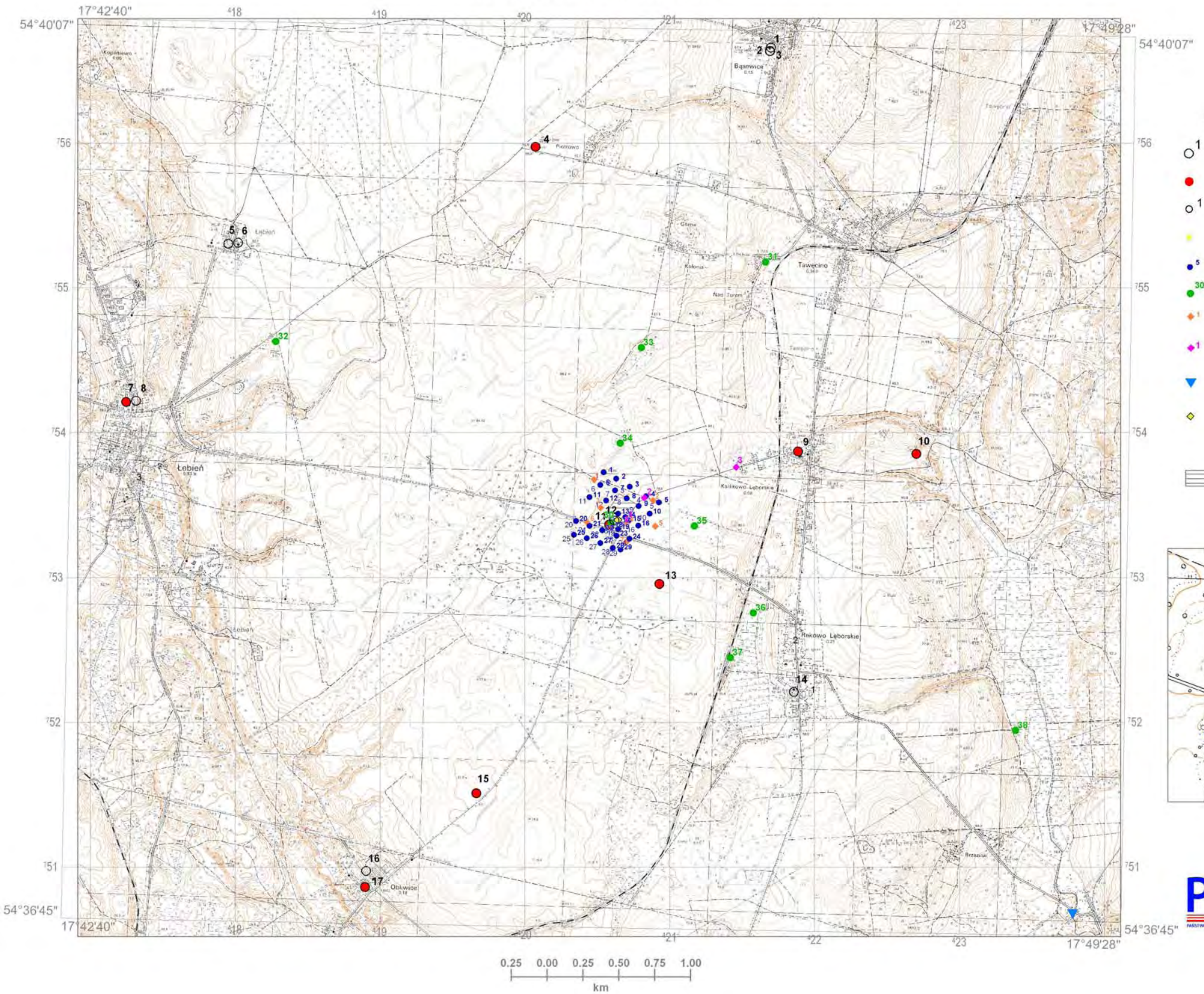
ANNEX No. 1

Documentation map in the scale 1:25 000



EXPLANATIONS

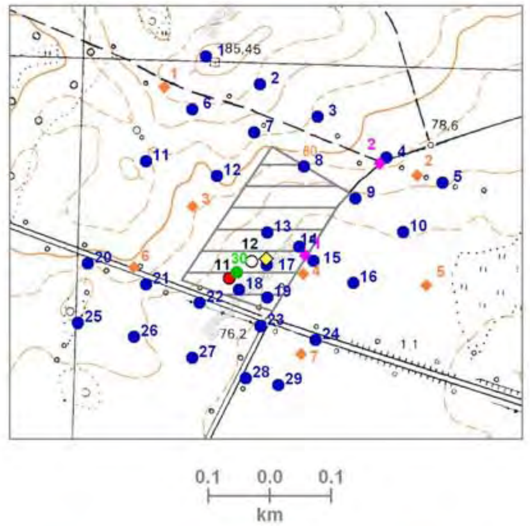
SAMPLED POINTS

Numbers as in Annexes no. 3, 4, 5, 8 and 9

- Drilled wells
- Sampled drilled wells
- Hand-dug well
- Sampled hand-dug well
- Sampling point for methane and radon in soil air
- Sampling point for methane in soil air
- Measurement point of air pollution
- Measurement point of noise emitted by equipment and installations
- Surface water sampling point
- LE-2H well

OTHERS

- Łebień drilling pad

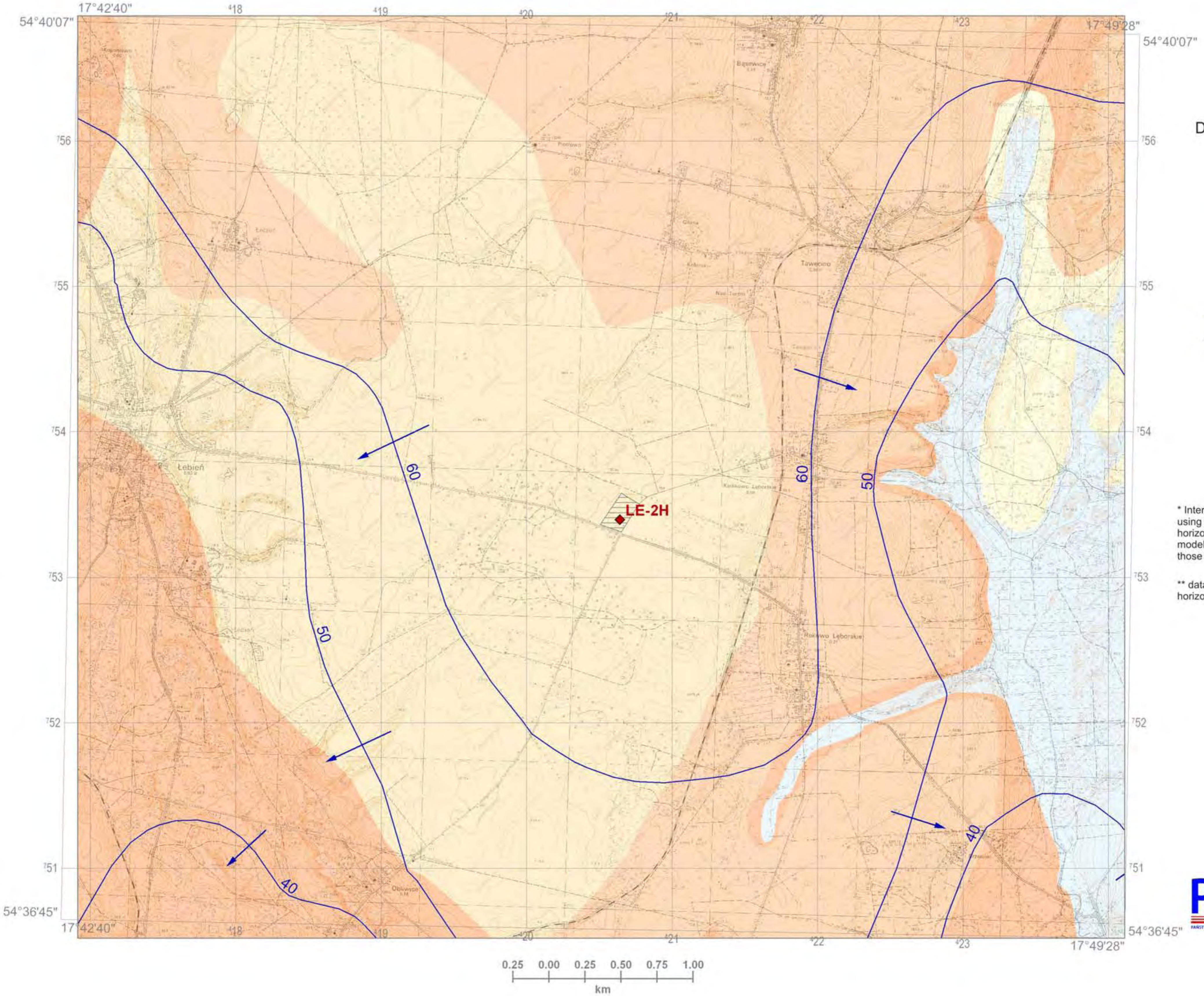


PSH

W zakresie dotyczącym wód podziemnych sfinansowano ze środków wypłaconych przez Narodowy Fundusz Ochrony Środowiska i Gospodarki Wodnej

ANNEX No. 2

Map of elements of hydrodynamics in the scale 1:25 000



EXPLANATIONS

DEPTH TO WATER-BEARING HORIZON*

- 5-10m
- <5m
- 10-20m
- 5-20m
- 20-50m

HYDRODYNAMICS

- 50 — Hydroisohypses of water-bearing horizon in m asl
- Local direction of groundwater flow

OTHERS

- Łebień drilling pad
- LE-2H well

* Interpretation of depth to water-bearing horizon was carried out using data from database GIS MhP 1:50 000 "First water-bearing horizon – distribution and hydrodynamics" and results of digital modeling (depths to water-bearing horizon may locally differ from those shown here)

** data from database GIS MhP 1:50 000 "First water-bearing horizon – distribution and hydrodynamics"

W zakresie dotyczącym wód podziemnych sfinansowano ze środków wypłaconych przez Narodowy Fundusz Ochrony Środowiska i Gospodarki Wodnej

ANNEX No. 3

Measurement points of air pollution and obtained results

Lp.		1	2	3	4	5	6	7	Reference concentrations*
No. as shown on map (Annex 1)		**3**	**4**	**5**	**2**	**1**	**6**	**7**	
Date / period		19.VII.2011	19.VIII.211	30.VIII.2011	VIII – IX 2011	VIII – IX 2011	VIII – IX 2011	VIII – IX 2011	
Measurement		Draeger CMS analyser	Draeger CMS analyser	Draeger CMS analyser	Passive samplers	Passive samplers	Passive samplers	Passive samplers	
Sulfur dioxide	**µg/m³**	< 517	< 517	< 517	6.05	6,3	5.9	20,2	350
Nitrogen dioxide		< 646	< 646	< 646	7,9	5,71	4,56	3,99	200
Benzene		< 259	< 259	< 259	0.58	1,03	0,6	0,59	30
Methane		< 25 860	< 25 860	< 25 860	-	-	-	-	3 000
Carbon monoxide		< 6 465	< 6 465	< 6 465	-	-	-	-	30 000
Sulfur hydrogen		< 259	< 259	< 259	-	-	-	-	20
Carbon dioxide	**ppm**	450	380	370	-	-	-	-	*Control value*

* After Regulation of the Minister of Environment of 26 January 2010 on reference values for certain substances in the air (Journal of Laws of 2010, No. 16, item 87

ANNEX No. 4

Measurement points of noise level and obtained results

Lp.	**No.** as shown on map (Annex 1)	Location	Results of measurements dB			Norms dB
			19.07.2011 ***before fracturing***	**19.08.2011** ***during fracturing***	**09.09.2011** ***during gas tests***	
1	**1**	Drilling pad boundary (at fence of technological area)	38,1	62,9 – 76,0	56,4	nn
2	**2**	By the road to Karlikowo Łęborskie village	36,9	68,6	48,3	nn
3	**3**	Close to houses of Karlikowo Łęborskie village	36,2	53,9	44,0	55,0

nn – not normalized

Results of measurements of methane and radon concentrations in soil gas

Lp.	No. as shown on map (Annex 1)	Coordinates WGS 84		Sampling depth in m bgs	CH_4 [ppm]	^{222}Rn [kBq]	Measurement date	Remarks
		N	E					
1	1	543827,67	174606,49	0,8	0	9,6	20.07.2011	
2	2	543826,26	174611,37	0,8	0	24,0	20.07.2011	
3	3	543824,62	174616,61	0,8	0	17,1	20.07.2011	
4	4	543822,53	174622,89	0,8	0	19,3	20.07.2011	
5	5	543821,27	174627,97	0,8	0	6,7	20.07.2011	
6	6	543824,89	174605,31	0,8	0	7,7	20.07.2011	
7	6	543824,89	174605,31	0,8	\		13.10.2011	
8	7	543823,74	174610,96	0,8	0	39,3	20.07.2011	
9	8	543822,01	174615,47	0,7	0	30,8	20.07.2011	
10	8	543822,01	174615,47	0,8	\	5,7	12.10.2011	
11	9	543820,37	174620,18	0,8	0	17,0	20.07.2011	
12	10	543818,66	174624,49	0,8	0	15,3	20.07.2011	
13	10	543818,66	174624,49	0,4	\	2,1	13.10.2011	
14	11	543822,12	174601,25	0,8	0	26,2	20.07.2011	
15	12	543821,42	174607,66	0,8	0	44,4	20.07.2011	
16	13	543818,50	174612,30	0,8	0	101,5	19.07.2011	
17	14	543817,80	174615,20	0,4	0	2,0	19.07.2011	
18	15	543817,07	174616,47	0,7	0	5,2	20.07.2011	
19	16	543815,95	174620,12	0,8	0	6,3	20.07.2011	
20	17	543816,80	174612,30	0,8	0	10,1	19.07.2011	
21	18	543815,50	174609,80	0,4	0	3,2	19.07.2011	
22	19	543815,00	174612,40	0,3	patrz uwagi	2,9	19.07.2011	*point localized in line of entrance to drilling pad area where power aggregate was formerly placed; results of individual measurements: 1) start: 600; mean value: 60-70; maximum value::803 2) 0 3) 0 4) 460 5) 352*
23	20	543816,74	174556,18	0,8	0	41,3	20.07.2011	
24	20	543816,74	174556,18	0,8	\	3,2	13.10.2011	
25	21	543815,68	174601,45	0,8	0	10,5	20.07.2011	
26	22	543814,78	174606,28	0,8	0	32,0	20.07.2011	
27	22	543814,78	174606,28	0,8	\	4,1	13.10.2011	
28	23	543813,62	174611,83	0,6	0	26,4	20.07.2011	
29	24	543812,95	174616,80	0,8	0	16,7	20.07.2011	
30	24	543812,95	174616,80	0,6	\	1,6	13.10.2011	
31	25	543813,63	174555,39	0,8	0	28,1	20.07.2011	
32	26	543812,94	174600,44	0,8	0	34,4	20.07.2011	
33	27	543811,90	174605,71	0,7	0	30,8	20.07.2011	
34	28	543810,88	174610,56	0,8	0	21,8	20.07.2011	
35	29	543810,55	174613,53	0,8	0	15,7	20.07.2011	
36	30	543816,10	174608,90	\	0	\	19.07.2011	*measurement of methane concentration in air accumulated in water well casing*
37	31	543915,30	174707,40	0,1	> 10 000	\	19.07.2011	*waterlogged soil along a creek (now there is no flow but soil remains water-soaked); soil air sampling possible on very shallow depths only results of methane measurements fall beyond the scale*
38	32	543855,60	174359,40	0,8	0	7,3	19.07.2011	
39	33	543855,70	174620,10	0,4	800	0,0	19.07.2011	
40	34	543834,20	174612,60	0,1	0	\	19.07.2011	*water-logged area; soil air sampling possible on very shallow depths only*
41	35	543816,00	174641,80	0,4	0	1,2	19.07.2011	
42	36	543756,90	174705,00	0,3	250	1,8	19.07.2011	
43	37	543746,80	174656,50	0,8	0	21,2	19.07.2011	
44	38	543731,60	174846,70	0,6	110	19,8	19.07.2011	

\ not studied

parameter/unit \ laboratory number		1014/11/14	1014/11/17	1014/11/18	1014/11/19	1014/11/23	1014/11/26	1014/11/27	1014/11/30
pH	**-**	6,35	5,80	5,73	6,63	6,72	6,01	6,15	7,47
specific electrical conductivity	**mS/cm**	12,14	13,76	15,41	53,10	123,40	49,60	45,40	11,93
total alkalinity	**mg $CaCO_3$/l**	173	199	221	293	417	260	202	136
total organic carbon (TOC)	**mg/l**	82	34	39	67	129	74	74	11
phenol index	**mg/l**	8	8	6	15	20	15	10	<2
cyanide	**mg/l**	<0,2	<0,2	<0,2	<0,5	<1,0	<0,5	<0,5	<0,2
anionic surfactants	**mg/l**	<0,5	8	6	13	31	11	11	1
F	**mg/l**	0,4	1,2	1,8	6,1	4,9	3,1	2,9	1,6
Cl	**mg/l**	4100	4500	5200	20000	48000	18000	16000	3800
NO_2	**mg/l**	0,5	0,8	0,6	1,8	4,2	1,7	1,6	0,6
Br	**mg/l**	25	40	50	200	500	180	160	40
NO_3	**mg/l**	0,5	0,5	0,5	2,2	7,1	2,3	2,5	0,4
HPO_4	**mg/l**	<3	<3	<3	<30	<90	<30	<30	<3
SO_4	**mg/l**	52	<5	<5	<50	<150	<50	<50	29
HCO_3	**mg/l**	211	243	270	357	509	317	246	166
NH_4	**mg/l**	9	12	14	57	159	52	46	11
B	**mg/l**	2,5	3,8	4,0	15,3	40,1	14,4	12,9	2,7
Ba	**mg/l**	5,3	10,4	14,7	75,4	217,9	70,1	60,8	13,1
Ca	**mg/l**	318	531	620	2793	7568	2648	2340	529
Cr	**mg/l**	<0,03	<0,03	<0,03	<0,03	<0,3	<0,03	<0,03	<0,03
Fe	**mg/l**	23,4	17,4	17,6	11,7	22,2	22,3	19,7	2,4
K	**mg/l**	82	123	130	228	536	276	255	51
Mg	**mg/l**	31	51	62	265	759	248	217	50
Mn	**mg/l**	1,44	1,24	1,78	4,51	11,32	5,99	7,07	1,09
Na	**mg/l**	2118	2164	2423	8871	22596	8425	7515	1685
P	**mg/l**	<0,5	<0,5	<0,5	<0,5	<5	<0,5	<0,5	<0,5
SiO_2	**mg/l**	17	24	18	32	67	34	33	14
Sr	**mg/l**	25,8	46,7	61,0	307,7	856,9	287,7	251,4	52,8
Ti	**mg/l**	<0,02	<0,02	<0,02	<0,02	<0,2	<0,02	<0,02	<0,02
Zn	**mg/l**	0,31	0,18	0,14	0,33	0,60	0,23	0,19	0,06
Hg	**µg/l**	<0,3	<0,3	<0,3	<0,3	<0,3	<0,3	<0,3	<0,3
Li	**µg/l**	685	987	1110	4753	11885	4696	3912	862
Be	**µg/l**	<1	<1	<1	<1	<1	<1	<1	<1
Al	**µg/l**	69	202	176	1039	93	711	587	142
Co	**µg/l**	<10	<10	<10	<10	<10	<10	<10	<10
Ni	**µg/l**	<50	<50	<50	<50	<50	<50	<50	<50
Cu	**µg/l**	<50	<50	<50	<50	<50	<50	<50	<50
Rb	**µg/l**	99	135	144	499	1190	484	423	105
Mo	**µg/l**	7	5	4	4	5	5	4	2
Ag	**µg/l**	<1	<1	<1	<1	1	<1	<1	<1
Cd	**µg/l**	<1	<1	<1	<1	<1	<1	<1	<1
Sn	**µg/l**	<2	<2	<2	<2	<2	<2	<2	<2
Sb	**µg/l**	<1	<1	<1	<1	1	<1	<1	<1
Pb	**µg/l**	<20	<20	<20	<20	<20	<20	<20	<20
U	**µg/l**	<1	<1	<1	<1	<1	<1	<1	<1

(shaded)	Values exceeding the highest admissible pollution indicators for treated industrial liquid waste as given in Annex 3 to the Regulation of the Minister of Environment of 24 July 2006 on conditions which must be complied while discharging waste water to water or soil and on substances particularly hazardous to aquatic environment.

laboratory no.	field no.	sampling date	description of sample
1014/11/10	2	18.08.2011	technological water from open-air reservoir no. 2, one day before fracturing
1014/11/14	5	31.08.2011	flowback fluid cleaned up after drilling through the plug 3
1014/11/17	8	01.09.2011	flowback fluid cleaned up after drilling through the plug 6
1014/11/18	9	08.09.2011	technological water from open-air reservoir no. 1, one day after drilling through at the plugs; flare stack burning gas
1014/11/19	10	08.09.2011	flowback cleaned up at filter station, one day after drilling through all the plugs; flare stack burning gas
1014/11/23	13	09.09.2011	flowback cleaned up at filter station, second day after drilling through all the plugs; flare stack
1014/11/26	16	11.09.2012	flowback cleaned up at filter station, five days after drilling through all the plugs; sample taken by Lane Energy
1014/11/27	17	16.09.2011	technological water from open-air reservoir no. 1, after nitrogen treatment, during gas tests
1014/11/30	20	26.09.2011	technological water from open-air reservoir no. 2, after closing the well and filtering the water from reservoir no. 1 to reservoir no. 2, before transportation to Warblino

ANNEX No. 7

Results of sampling of surface water

No.	Indicator	Sampling on 19.07.2011 r.	Sampling on 30.08.2011 r.	Sampling on 20.09.2011 r.	Norms*
1	pH	8,1	7,7	7,8	6-8,5
2	dissolved oxygen (mg/l)	9,78	10,19	9,87	>7
3	biological oxygen demand, BOD5 (mg/l)	1,4	1,1	1,4	<3
4	chlorides (mg/l)	10,9	11,8	11,7	<200
5	sulfates (mg/l)	36,4	36,9	33,7	<150
6	sodium (mg/l)	0,592	5,69	5,67	nn
7	potassium (mg/l)	3,07	1,76	1,86	nn
8	sum of nitrite nitrogen and nitrate nitrogen (mg/l)	1,58	1,49	1,65	nn
9	total Kjeldahl nitrogen (mg/l)	0,756	1,02	0,825	2
10	total nitrogen (mg/l)	2,34	2,51	2,48	<5
11	total organic carbon (mg/l)	4,27	4,49	5,19	<10
12	sum of hydrocarbons C10 – C40 (mg/l)	<0,1	<0,1	<0,1	<0,2
13	boron (mg/l)	<0,010	<0,01	<0,01	<2
14	anionic detergents (mg/l)	<0,1	<0,1	<0,1	nn
15	non-ionic detergents (mg/l)	<1,0	<1,0	<1,0	nn
16	sulfides (mg/l)	0,11	<0,04	<0,04	nn

no – not determined
nn – not normalized

* Regulation of the Minister of Environment of 20 August 2008 on the method of classification of the status of uniform body of surface water (Journal of Law 2008, no. 162, item 1008)

ANNEX No. 8

Results of measurements of hand-dug water wells before fracturing

No. of hand-dug well as shown in Annex 1	GPS coordinates		Locality	User	Ordinate of land surface [m in asl]	Water-bearing horizon					Uwagi
	φ	λ				Stratigraphy	Depth to water table [m]	Depth to the bottom [m]	Ordinate of water table [m in asl]	Data pomiaru [dd-mm-rrrr]	
1	54°37’38.1”	17°47’26.3”	Rekowo Lęborskie	Private	68,50	Q	1,56	5,80	66,94	30.06.2011	*old post-German well, unused, in poor shape*
2	54°37’48.5”	17°47’18.6”	Rekowo Lęborskie 26/2	Private	75,00	Q	3,21	8,70	71,79	30.06.2011	*old stone-lined well in continuous use*
3	54°38’22.7”	17°43’04.9”	Łebień 5/1	Private	60,00	Q	3,40	4,60	56,60	1.07.2011	*well-secured, used for watering*

No. of drilled wells		GPS coordinates		Locality User	Drilling				Water-bearing horizon				Remarks
as shown in map (Annex 1)	after HYDRO database	φ	λ		Year of complet-ion	Stratigraphy of basal sediments	Depth [m]	Ordinate of land surface [in m asl]	Stratigraphy	Depth to the top [m] A M	Depth to water table [m] A M	Measurement date [dd-mm-yy] A M	
1	40022	54°40'03.3"	17°47'08.0"	Bąsewice local intake	1966	Q	88,0	78,50	Q	78,60 -	13,00 -	1966 -	*unused, closed*
2	40043	54°40'02.5"	17°47'07.6"	Bąsewice local intake	1972	Q	94,0	76,80	Q	80,00 -	12,60 -	1972 -	*unused, closed*
3	-	54°40'02.5"	17°47'07.7"	Bąsewice local intake	-	Q	105	76,60	Q	-	-	-	*unused, closed no data in CBDH database*
4	130033	54°39'40.2"	17°45'38.0"	Tawęcino village intake	1969	Q	51,0	94,30	Q	33,00 -	29,80 -	1969 -	*used, closed*
5	120026	54°39'17.3"	17°43'40.3"	Łebień farm well	1968	Q	41,5	82,50	Q	27,00 -	16,60 17,50	1968 01.07.2011	*unused*
6	-	54°39'17.56"	17°43'44.07"	Łebień	-	-	-	-	-	- -	- -	- -	*unused, closed, no data in CBDH database, site inspection*
7	120044	54°38'41.50"	17°43'02.07"	Łebień village intake	1972	Q	34,0	61,10	Q	17,20 -	10,70 -	1972 -	*used*
8	120009	54°38'41.8"	17°43'05.9"	Łebień health service center	1962	Q	31,5	60,00	Q	18,00 -	10,00 -	1962 -	*unused, liquidated, filled up*
9	-	54°38'33.1"	17°47'21.1"	Karlikowo Lęborskie private use	-	Q	24,0	70,20	Q	- -	- 9.00	- 20.07.2011	*used*
10	130162	54°38'33.0"	17°48'06.7"	Karlikowo Lęborskie farm well	2010	Q	44,7	63,50	Q	41,00 -	5,50 -	2010 -	*used*
11	130157	54°38'16.1"	17°46'08.9"	Łebień LE1 drilling pad well no. 1	2010	Ng	50,0	76,64	Q	16,40 -	16,40 -	30.04.2010 -	*used*
12	130158	54°38'17.0"	17°46'10.4"	Łebień LE1 drilling pad well no. 2	2010	Ng	52,0	75,93	Q	15,60 14,40	15,60 14,40	30.04.2010 30.06.2011	*used,* *on standby if necessary*
13	-	-	-	Łebień Rolland Sp. z o.o.	2001	Q	61,0	78,70	Q	54,00 -	17,60 17,24	2001 11.08.2011	*documentation data, no data in CBDH*
14	130051	54°37'39.4"	17°47'21.1"	Rekowo Lęborskie village intake	1973	Q	65,0	68,00	Q	41,00 -	10,00 -	1973 -	*unused, closed*
15	-	54°37'15.5"	17°45'19.6"	Obliwice Rolland Ltd. well no.2	-	Q	20,0	81,00	Q	-	8,00	-	*data provided by owner, no data in CBDH database*
16	120081	54°36'57.7"	17°44'37.7"	Obliwice Rolland Ltd. well no.1	2000	Q	25,0	50,90	Q	8,50 -	2,70 3,35	2000 21.07.2011	*used*
17	120030	54°36'54.1"	17°44'37.4"	Obliwice village intake	1969	Ng	52,0	56,90	Ng	33,50 -	3,10 -	1969 -	*used, closed*

ANNEX 10

Seismic monitoring of hydraulic fracturing performed on the Łebień LE-2H well

Seismic monitoring of hydraulic fracturing performed on the Łebień LE-2H well

Task completed in accordance with Annex no. 1/259 of 15 July 2011 to the Project "Monitoring of seismic risk in the area of Poland", performed at the order of the Minister of Environment and financed by the National Fund of Environmental Protection and Water Management (Agreement no. 445/2007/Wn-07/F6-bp-tx/D)

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Warsaw, 10 October 2011

Preliminary remarks

Vivid discussions on prospecting and exploration of shale gas resources in Poland have raised concerns about potential threats and risks for the natural environment. The threats mainly included risks of groundwater pollution but there were also raised concerns of negative potential consequences of induced seismic quakes. In the last years the news media reported some quakes accompanying exploitation of shale gas resources. There is growing evidence that such reports from the United States and Canada and more recently Great Britain aroused deep concern for public opinion. This resulted in growth of public expectations that relevant government agencies will take care of safety and establish close supervision of prospecting and subsequently exploitation of shale gas resources. In order to meet these expectation, the Polish Ministry of Environment charged the Institute of Geophysics with the task to carry out seismic monitoring hydraulic fracturing operations performed on the LE-2H well near Łebień (the Nowa Wieś Lęborska commune, Lębork District, Pomeranian Voivodeship). The operations were conducted in an area for which Lane Energy Poland Ltd. holds a concession for exploration.

The fracturing treatment of a horizontal section of the LE-2H exploratory well was the first operation of that type performed in Poland. The borehole has not been completed as exploratory but a production well despite of the type of concession. The seismic monitoring of the fracturing treatment was also conducted for the first time in Poland. Therefore, this operation had to be treated as an experiment and, therefore, arranged and conducted with great care. The monitoring operation was aimed at recording eventual seismic effects of the fracturing treatments.

The task made it necessary to suspend temporarily a part of seismic surveys conducted in regions previously selected for carrying out the Project *Monitoring of seismic risks in the area of Poland* and move several seismic stations to the Łebień LE-2H well site region. The time from ordering this task to the start of surveys was very limited what created a real challenge for both the logistics and financial side of the operation, especially as tasks defined in the Annex to the Agreement were new and, not taken into account in the original budget of the Project. The surveys were conducted using 10 seismic stations placed at distances ranging from 1 to 25 km from the Łebień LE-2H well. That spacing was chosen in order to make possible recording eventual weak quakes coming from the well as well as recording and localization of stronger quakes if they occur. The criteria in selecting places for location of the seismic stations mainly included the level of seismic background noise and technical and logistic possibilities of placing a given station. All these factors appeared important and the final distribution of the seismic survey network turned to be a net result in attempts to match all these requirements. Figure 1 shows the final location of all the ten stations.

The recording started on 15 July 2011 to define the level of seismic background seismic before the beginning of hydraulic fracturing treatments. These treatments began on on 19 August to be continued till 28 August 2011. During that time a team of specialists stayed in the Łebień area to take care of appropriate course of the recordings and take immediate action in the case of any failure of the equipment. From 28 to 30 August, the operator of the Łebień LE-2H well conducted technological works to test effectiveness of the fracturing treatments. The seismic surveys were continued for one more month, till the end of September, to record any eventual quakes which would occur with delay. After the end of the recordings, the seismic stations were dismantled and taken back to their earlier locations in order to continue the major tasks of the Project.

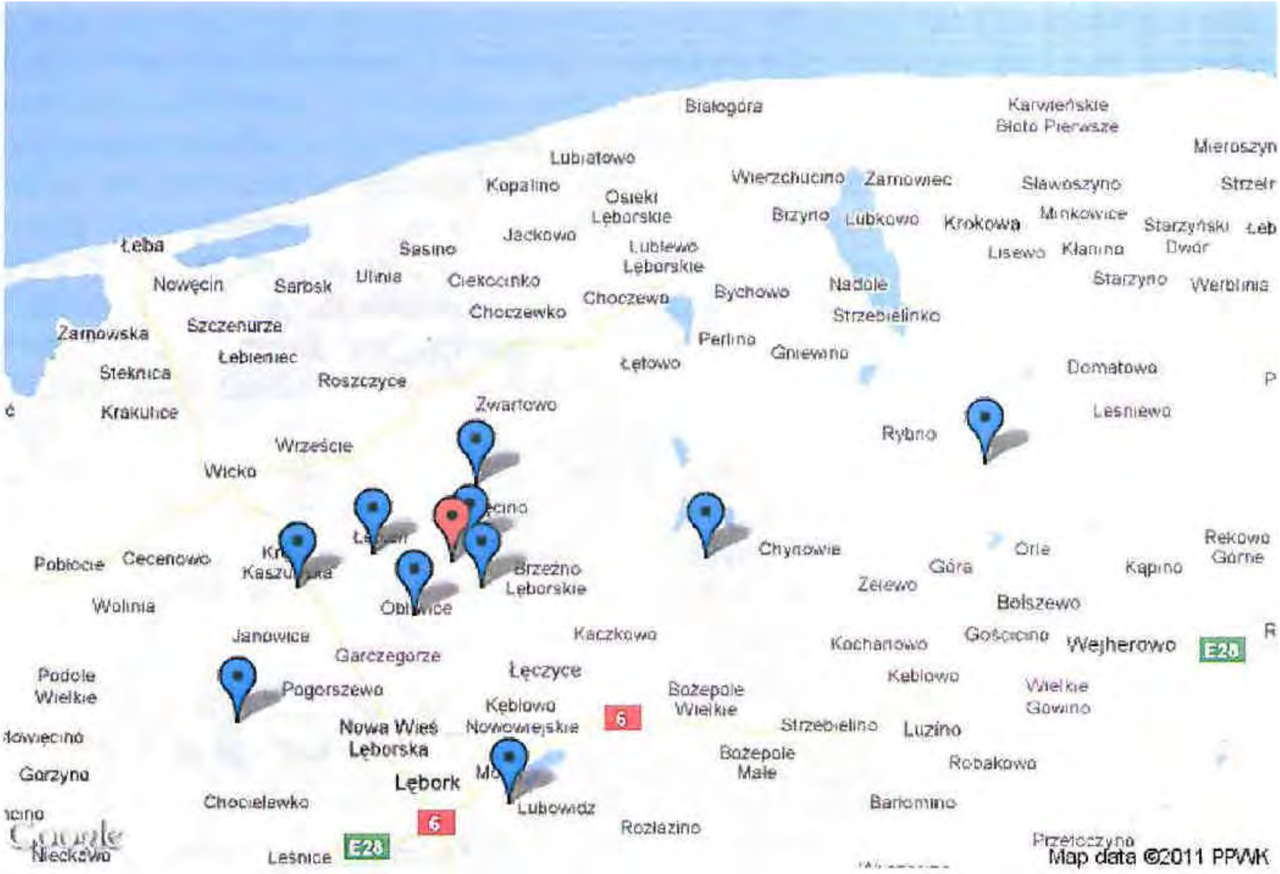

Fig. 1. *Map of area of the Łebień LE-2H (red drawing pin) and location of the seismic stations (blue drawing pins).*

Data processing

The recordings were to be conducted in area of high level of background noise and at the same time aimed to trace very weak seismic events what made it necessary to use untypical approach in data analysis, Typical tools used in seismology for detecting quakes here appeared useless because they are adjusted for detection of strong phenomena with a higher signal-to-noise ratio and different frequency characteristics. The recordings from the whole time period of monitoring of the fracturing treatments were processed using a special software written by the Institute of Geophysics. This software is based on the concept of artificial neural network. It was developed for over 10 years and currently markedly improved thanks to data and experience gathered from conducting the Project *Monitoring of seismic risks in the area of Poland.*

The software and concept and algorithm were presented in more detail by J. Wiszniewski's paper *Application of real time recurrent neural network for seismic event detection* (Acta Geophysica Polonica, 2000, vol. XLVIII, no. 1). The software uses the concept of real time recurrent network (RTRN) adjusted for analysis of passes in real time. Neural network of the RTRN type is built of recurrent neurons with outlets connected with their own inlets to form a feedback. Feedback signals of recurrent neurons are here directed back to the inlets with a delay for one time period

.

This neural network makes it possible to identify time sequences of any length. From the mathematical point of view, such artificial neural network is a system of equations with coefficients which have to be selected. These coefficients are determined by the learning method based on correcting their values to minimize error between the expected value and real value of outlet of the neural network. The neural network learning is based on training data, including a group of data referring to real seismic phenomena and another one, referring to seismic disturbances related to man's activities. Appropriately prepared neural network makes possible detection of phenomena so weak that their amplitude does not exceed that of noise. The use of time correlations between seismic stations enables efficient elimination of accidental disturbances. The network was learned on data coming from the Project *Monitoring of seismic risks in the area of Poland.* Estimations made on test data showed that its efficiency is about 85%, which means that such per cent of real phenomena should be detected. However, so high efficiency results in relatively high (about 60%) share of false detections. This makes necessary for geophysicists to carry out arduous verifications of all the detections but this method remains most efficient in detection of weak quakes.

The importance of the present task made it also necessary to conduct detailed visual inspection of all the recordings made during the fracturing operations.

Results of recordings

The studied are is situated at a distance of about 20 km from the sea which generates microseism vibrations with frequencies which are sensed at seismic stations. Moreover, high population density in Poland is responsible for strong influence of anthropogenic disturbances which often coincide with the band of seismic vibrations. This effect is well shown by comparison of recordings of amplitude of microseismic noise during the daytime and at night. During the daytime the mean amplitude is about two times higher and there occur numerous short-lasting high amplitude disturbances. Figure 2 shows examples of records made during the daytime and at night.

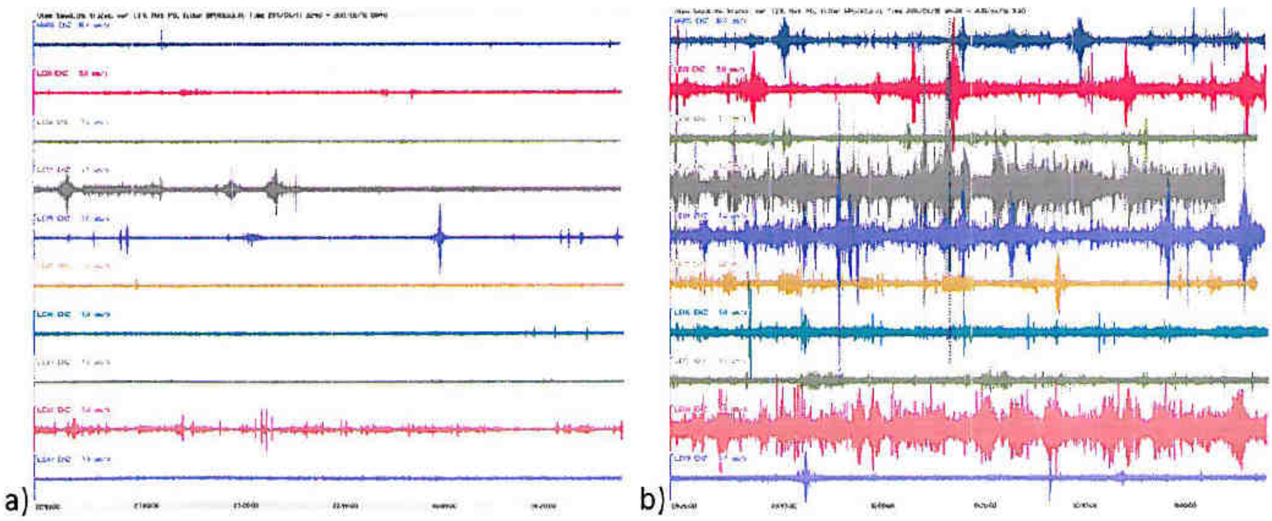

Fig. 2. *Difference in noise level at night (a) and during the daytime (b).*

The neural network was used in analysis of data gathered during the whole time of monitoring of the vicinities of Łebień. Table 1 shows the obtained results.

Table 1. Results of detection of seismic phenomena recorded in the course of monitoring of the Łebień LE-2H well.

Number of detections	Correct detections	Teleseismic quakes	Regional quakes
1712	52	46	6

High number of generated detections is mainly due to disturbances recorded by several stations. Figure 3 shows examples of records of such phenomena which were recorded by all the stations in the Łebień area. Such disturbance consisted of a series of impulses propagating at acoustic velocities what excludes seismic nature of these phenomena. Source of these impulses was situated to the east of the Łebień area and active a few hours per day. Its activity was recorded several times in the course of the monitoring.

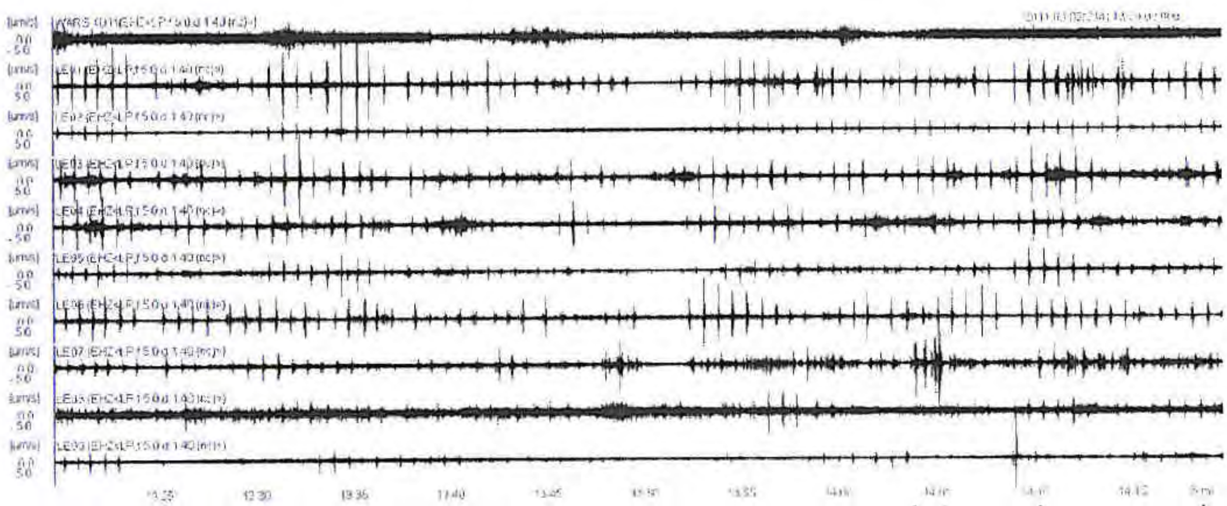

Fig. 3. *An example of record of disturbances coming from beyond the Łebień LE-2H well area and generating numerous false detections traced by the neural network.*

Out of 52 of the recorded real quakes, the majority represented distant earthquakes (teleseismic phenomena) and only six – regional quakes.

Throughout the whole time of monitoring of the Łebień LE-2H well, there were not recorded any local seismic phenomena which could be linked with the hydraulic fracturing treatments.

The studied well is located in area of tectonically stable East-European (Precambrian) Platform. Such location markedly reduces probability of occurrence of any quakes because of the lack of active faults which could act as a source of quakes induced by the hydraulic treatment.

The only measurable effect was a paraseismic signal recorded by the seismic station closest to the well (about 1 km distant). The installations working at the drilling pad (mainly pumps) were the source of that signal. The signal was similar to that of seismic background noise in character but its amplitude was about two times higher. A single stage of the fracturing treatment lasted for about 2 hours. An example of record of such stage is given in Fig. 4. From 19 to 28 August 2011, thirteen stages of the fracturing treatments were recorded. The treatments were followed in the next two days by technical tests on the well and the whole hydraulic fracturing process may be regarded as completed on 30 August 2011. For comparison, a distant seismic quake recorded by the same seismic station is here shown using the same amplitude scale (wave velocity [µm/s]).

Despite of large distance (in the order of thousands of km), the quake from the Fiji region gave amplitudes ten times high than the fracturing monitored from a distance of about 1 km and, nevertheless, it was not felt by people in the Łebień area.

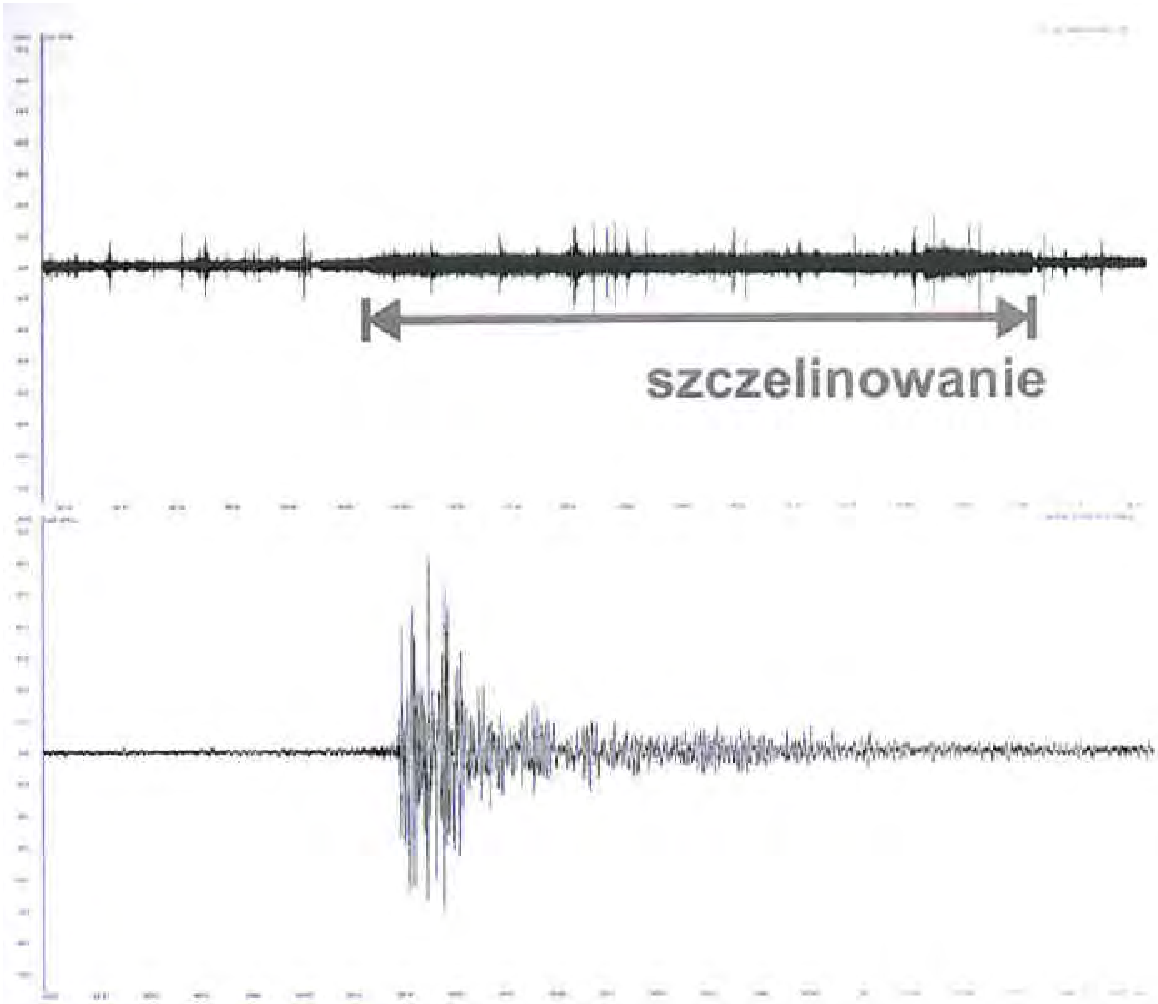

Fig. 4. *Record of fracturing treatment performed in one of intervals of the horizontal well section, which lasted for about 2 hours. Note slight increase in amplitude of signal (above). Earthquake in the Fiji area, magnitude of M 7.3, distance from epicenter of about 15 000 km, date and origin time according to the source – 15/09/2011, 19:31:02.0 UTC (below). Both phenomena are presented in the same scale of amplitude (wave velocity in µm/s).*

Effect on human health and buildings

In Poland, effect of vibrations on human health and buildings is defined in two building norms: PN-88/B-02171 – *Estimation of the impact of vibrations on people in buildings*,
and PN-85/B-02170 – *Assessment of harmfulness of vibrations transmitted by substrate to buildings.* In accordance with first of these norms, accelerations lower than 5 mm/s^2 do not pose any physical or health hazard for people. According to the second norm, effect of inertia force on a building may be completely neglected when amplitude of horizontal ground acceleration does not exceed 0.005 of the Earth acceleration, that is about 50 mm/s^2 whereas the maximum amplitudes of accelerations recorded during the fracturing operations were below 0.5 mm/s^2**.**

Therefore, vibrations generated by equipment working in time of the fracturing operations did not pose any risk for human health and buildings in the neighboring areas.

Summary and final conclusions

The process of hydraulic fracturing is highly dependent on local geological conditions. Therefore, a part of conclusions drawn from the monitoring of the Łebień Le-2H well refers only to these fracturing operations whereas others are more general in character.

1. Conclusions concerning the fracturing operations at Łebień on 18-28 August 2011:

- There were not recorded any seismic quakes which could be linked with the fracturing operations.
- The studies carried out during four weeks before the fracturing and four weeks after the fracturing also did not detect any quakes.
- Ground vibrations generated by equipment working at the drilling pad do not pose any risk for human health and buildings.

2. Conclusions of general character:

- Quakes accompanying the fracturing operations are very weak which makes their detection at the ground surface very difficult or even sometimes impossible.
- Stronger phenomena which may be detected at the ground surface and subsequently localized are very rare.
- Quakes which may be felt by people are extremely rare in areas of exploitation of shale gas resources and their direct connection with the fracturing operations as a rule is not confirmed unequivocally.
- Occurrence of quakes largely depends on geological structure at the site of the fracturing operations, especially on presence of natural faults.
- Information on natural seismicity of the studied area is of utmost importance for subsequent assessments of impact of shale gas exploitation on eventual increase of seismic activity.

Seismicity induced by the fracturing operations is very low but there may occur stronger phenomena which may be related to these processes. According to some reports, there were some increase of seismic activity in areas of shale gas exploitation, for example in Lancashire (Great Britain) or British Columbia (Canada). However, any unequivocal confirmation of increase in seismic activity would require knowledge how active was a give area in the past. In the case of Poland and other areas of low seismic activity this would require to start monitoring well ahead of the beginning of shale gas exploitation. Such early start of monitoring will allow to gather data needed for unequivocal confirmation or rejection of assumed seismic risks related with shale gas exploitation.

ANNEX 11

Studies of hydrocarbon background in soil gas and analyses of shale gas for defining parameters making possible explanation of origin of potential occurrences of natural gas outside installation

INTRODUCTION

The report “Studies of hydrocarbon background in soil gas and analyses of shale gas for defining parameters making possible explanation of origin of potential occurrences of natural gas outside installation” was compiled in accordance with the Agreement No. 603/2011/6 concluded between the State Treasury – Ministry of Environment and Oil and Gas Institute.

Major points of that work included:

- Establishment of network of sampling points around the Łebień LE-2H well site (Figs. 1-2).
- Taking soil gas samples (40 samples) in the field with the use of the Institute equipment (sampling set).
- Taking two shale gas samples in an interval of a few days after completion of fracturing treatments on the Łebień LE-2H well.
- Transport of samples in Tedlar air sample bags to the laboratory.
- Chromatographic analysis for determination of molecular composition of gas.
- GCIRMS analysis for determination of composition of stable carbon isotopes in methane, ethane and carbon dioxide.
- Processing and tabulation of results and compilation of the final report.

The report presents the results of studies, description of methods used in the studies and specifications of samples taken for analysis.

I. Methodology of soil gas sampling

The studies were conducted using one of techniques of “free gas” spatial distribution mapping, based on sampling soil gas to determine presence and concentration of methane.

Such method is most often used in:

- monitoring tightness of underground gas storage reservoirs of natural gas,
- monitoring tightness of communal waste disposal facilities,
- assessing effectiveness of reconstruction or liquidation of gas wells, conducted before and after completion of works,
- assessing effectiveness of cementation of gas wells, conducted before and after completion of works,
- detection of gaseous exhalations of geogenic and anthropogenic origin,
- leak detection from the natural gas pipelines,
- assessing environmental impact of exploitation of oil and gas reserves,
- assessing environmental impact of liquidation of methane coal mines with high methane content in the coal,
- studies on explosive and toxic gases in environmentally degraded areas,
- determinations of soil gas composition in areas designated for urban development and housing.

The works carried out with the use of this method include:

Preparatory works:

- collection and analysis of essential, basic documentation (geodetic, geological and geochemical) for the area of the planned studies,
- designing distribution of measurement points for the gas mapping,
- analysis of results and compilation of research report summarizing results of the studies.

Field works:

- site inspection and interviews with local people,
- drilling monitoring wells in accordance with the designed distribution of measurement points,
- placing probes tightly in wells and tagging with basic probe setting data (region, symbol and number of measurement point),
- taking gas samples for analysis,
- securing the samples and transport to the analytical laboratory.

Taking soil gas samples during surveys of the Łebień area

Samples for analysis were taken by Jerzy Dudek, Piotr Klimek and Grzegorz Kołodziejak of the Recoverable Energy Technologies Division of the Oil and Gas Institute on 5 – 7 and 12-13 September 2011.

Gas sampling holes were made with Waecker BH23 gas powered jackhammer with a probing set including tubular drill rods with tapered thread, taper screwed to a drill rod and adapter for screwing the rods together.

Wells were drilled down to about 2 m depth using screw drill rods, the first of which had a conducting taper. When drilling was completed, drill rods were removed using drill mast with a single pipe arm with lifting capacity of 20 kN, After completion of a well, probe was inserted. The probe consisted of polyethylene (PE) pipe with blind upper end and fitted with tight seal and connector pipe for taking soil gas sample with the use of air aspirator. The probe was was placed in such a way that the whole tight seal was hidden in the well. Moreover, the ground around outlet of well was beaten down to closely adhere to the probe. Soil air was flowing into the soil gas probe by natural diffusion. Soil gas samples were taken to Tedlar bags with the use of pump with rotameter of MODEL 1067 SUPELCO AIR SAMPLER, made in the U.S.A. A gas mixture was drawn in from the probe with the use of pump to be subsequently injected to containers (Tedlar bags) 1 to 3 liters in volume. After filling up a container with soil gas, its valve was closed and the container sent to the Oil and Gas Institute Laboratory for analytical tests.

Note: The time from installation of probe to taking soil gas samples was dependent on several factors, such as progress in field works in the studied area.

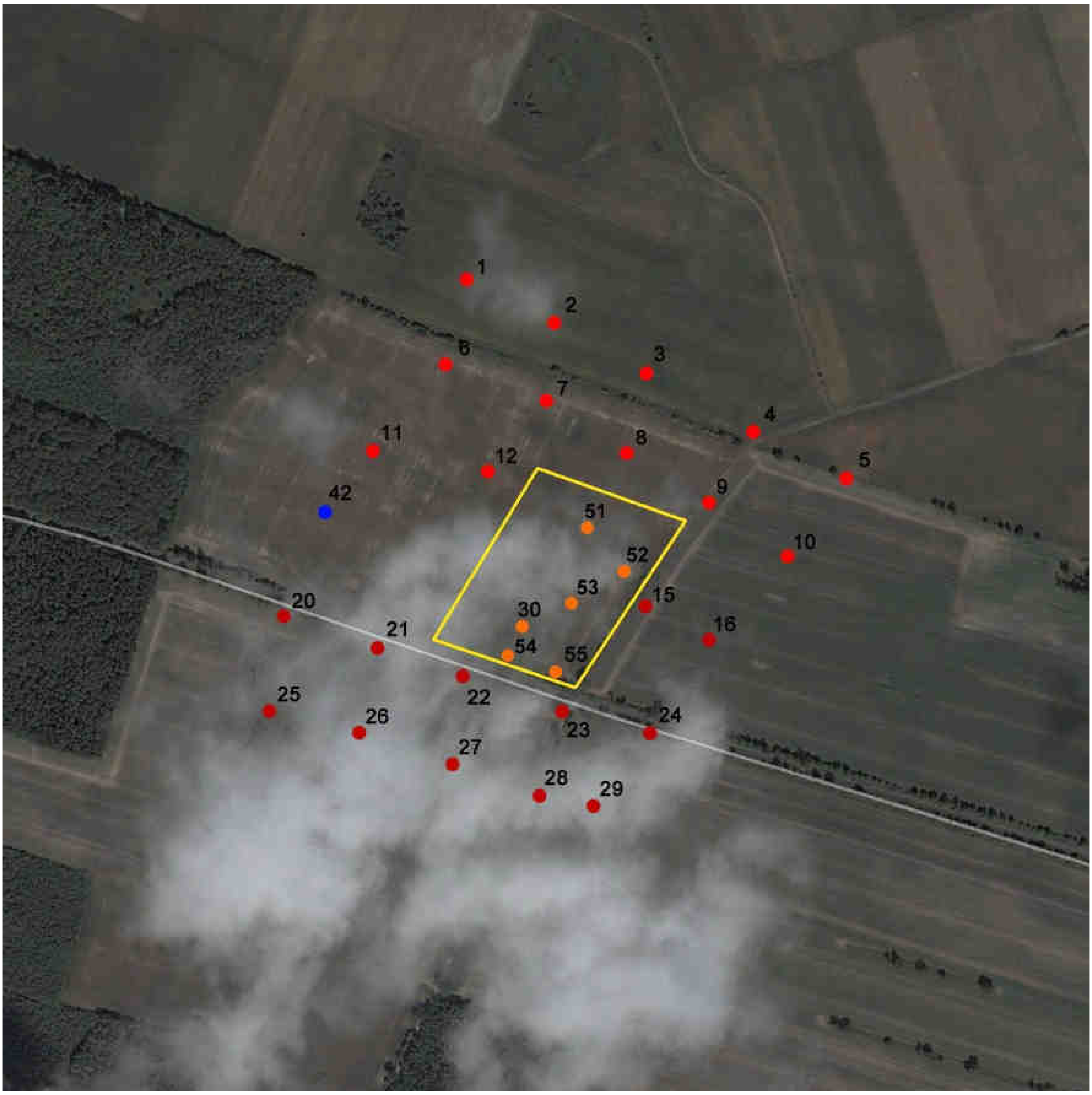

Fig. 1. Location of measurement points around the Łebień LE-2H drilling pad, in which soil gas monitoring was conducted

Fig. 2. Location of measurement points located at distances over 1 000 m from the Łebień LE-2H drilling pad. The points are shown on the map in accordance with sampling protocols.

Fig. 3. Area around the drilling pad.

Fig. 4. Drilling wells 2 m deep for installing probes.

Fig. 5. Field works in swampy area.

Fig. 6. Probe installed for soil gas sampling.

Fig. 7. Taking soil gas samples to the Tedlar bag.

Field sampling protocols

the original is given
a form translated below

Monitoring of soil air

Protocol no.

<table>
<tr><td>No. of measurement point</td><td colspan="9"></td></tr>
<tr><td rowspan="2">Coordinates of point</td><td>N</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>E</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Date of well completion</td><td colspan="9"></td></tr>
<tr><td>Hour of well completion</td><td colspan="9"></td></tr>
<tr><td>Depth of well</td><td colspan="9">m bgs (below the ground surface)</td></tr>
<tr><td colspan="10">Sampling</td></tr>
<tr><td>Date of sampling</td><td colspan="9"></td></tr>
<tr><td>Time of sampling</td><td colspan="9"></td></tr>
<tr><td>Sampling depth
(range)</td><td colspan="9">m bgs (below the ground surface)</td></tr>
<tr><td rowspan="4">Type of container*</td><td colspan="9">Tedlar bag 1 dm^3 in volume</td></tr>
<tr><td colspan="9">Tedlar bag 2 dm^3 in volume</td></tr>
<tr><td colspan="9">SUPELCO glass pipette</td></tr>
<tr><td colspan="9">GLIWICE glass pipette</td></tr>
</table>

* To be marked-up

INSTYTUT NAFTY I GAZU

Monitoring powietrza glebowego

Protokół nr 1/2579/SN

Nr punktu pomiarowego	31
Współrzędne punktu	N 54 39 14 8 E 17 47 07 4
Data wykonania otworu	05.09.2011
Godzina wykonania otworu	10:00
Głębokość otworu	2,0 m ppt
Pobór próby	
Data poboru	05.09.2011
Godzina poboru	18:15
Głębokość poboru próby (zakres)	1,0 – 2,2 m ppt
Rodzaj pojemnika*	**worek tedlarowy 1dm^3** worek tedlarowy 2 dm^3 pipeta szklana „SUPELCO” pipeta szklana „GLIWICE”

* - zaznaczyć

UWAGI:

INSTYTUT NAFTY I GAZU

Monitoring powietrza glebowego

Protokół nr 2/2579/SN

Nr punktu pomiarowego	33
Współrzędne punktu	N 54 38 56 4 E 17 46 21 7
Data wykonania otworu	05.09.2011
Godzina wykonania otworu	10:15
Głębokość otworu	2,0 m ppt
Pobór próby	
Data poboru	05.09.2011
Godzina poboru	18:25
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* - zaznaczyć

INSTYTUT NAFTY I GAZU

Monitoring powietrza glebowego

Protokół nr 3/2579/SN

Nr punktu pomiarowego	38
Współrzędne punktu	N 54 37 32 1 E 17 48 46 1
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Godzina wykonania otworu	10:45
Głębokość otworu	2,0 m ppt
Pobór próby	
Data poboru	05.09.2011
Godzina poboru	18:00
Głębokość poboru próby (zakres)	1,0 – 2,0 m ppt
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* - zaznaczyć

INSTYTUT NAFTY I GAZU

Monitoring powietrza glebowego

Protokół nr 4/2579/SN

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Współrzędne punktu	N	54	37	47	0					
	E	17	6	57	5					
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Pobór próby										
Data poboru	05.09.2011									
Godzina poboru	17:30									
Głębokość poboru próby (zakres)	1,0 – 1,8 m ppt									
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* - zaznaczyć

INSTYTUT NAFTY I GAZU

Monitoring powietrza glebowego

Protokół nr 5/2579/SN

Nr punktu pomiarowego	35								
Współrzędne punktu	N	54	38	16	2				
	E	17	46	41	0				
Data wykonania otworu	05.09.2011								
Godzina wykonania otworu	11:55								
Głębokość otworu	1,9 m ppt								
Pobór próby									
Data poboru	05.09.2011								
Godzina poboru	19:00								
Głębokość poboru próby (zakres)	1,0 – 1,9 m ppt								
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* - zaznaczyć

INSTYTUT NAFTY I GAZU

Monitoring powietrza glebowego

Protokół nr 6/2579/SN

Nr punktu pomiarowego	34								
Współrzędne punktu	N	54	38	35	1				
	E	17	46	13	2				
Data wykonania otworu	05.09.2011								
Godzina wykonania otworu	12:15								
Głębokość otworu	1,9 m ppt								
Pobór próby									
Data poboru	05.09.2011								
Godzina poboru	18:45								
Głębokość poboru próby (zakres)	1,0 – 1,9 m ppt								
Rodzaj pojemnika*	**worek tedlarowy 1dm^3** worek tedlarowy 2 dm^3 pipeta szklana „SUPELCO” pipeta szklana „GLIWICE”								

* - zaznaczyć

INSTYTUT NAFTY I GAZU

Monitoring powietrza glebowego

Protokół nr 7/2579/SN

Nr punktu pomiarowego	39								
Współrzędne punktu	N	54	38	06	4				
	E	17	46	01	2				
Data wykonania otworu	05.09.2011								
Godzina wykonania otworu	12:40								
Głębokość otworu	1,8 m ppt								
Pobór próby									
Data poboru	05.09.2011								
Godzina poboru	14:50								
Głębokość poboru próby (zakres)	1,0 – 1,8 m ppt								
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* - zaznaczyć

INSTYTUT NAFTY I GAZU

Monitoring powietrza glebowego

Protokół nr 8/2579/SN

Nr punktu pomiarowego	40								
Współrzędne punktu	N	54	37	58	1				
	E	17	45	52	5				
Data wykonania otworu	05.09.2011								
Godzina wykonania otworu	13:00								
Głębokość otworu	2,0 m ppt								
Pobór próby									
Data poboru	05.09.2011								
Godzina poboru	14:45								
Głębokość poboru próby (zakres)	1,0 – 2,0 m ppt								
Rodzaj pojemnika*	**worek tedlarowy 1dm^3** worek tedlarowy 2 dm^3 pipeta szklana „SUPELCO” pipeta szklana „GLIWICE”								

* - zaznaczyć

Monitoring powietrza glebowego

Protokół nr 9/2579/SN

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Współrzędne punktu	N 54 37 51 4 E 17 45 44 9
Data wykonania otworu	05.09.2011
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Głębokość otworu	2,0 m ppt
Pobór próby	
Data poboru	05.09.2011
Godzina poboru	14:45
Głębokość poboru próby (zakres)	1,0 – 2,0 m ppt
Rodzaj pojemnika*	**worek tedlarowy 1dm^3** worek tedlarowy 2 dm^3 pipeta szklana „SUPELCO” pipeta szklana „GLIWICE”

* - zaznaczyć

INSTYTUT NAFTY I GAZU

Monitoring powietrza glebowego

Protokół nr 10/2579/SN

Nr punktu pomiarowego	28
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Data wykonania otworu	05.09.2011
Godzina wykonania otworu	13:45
Głębokość otworu	2,0 m ppt
Pobór próby	
Data poboru	05.09.2011
Godzina poboru	19:00
Głębokość poboru próby (zakres)	1,0 – 2,0 m ppt
Rodzaj pojemnika*	**worek tedlarowy 1dm^3** worek tedlarowy 2 dm^3 pipeta szklana „SUPELCO” pipeta szklana „GLIWICE”

* - zaznaczyć

INSTYTUT NAFTY I GAZU

Monitoring powietrza glebowego

Protokół nr 11/2579/SN

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Współrzędne punktu	N 54 38 10 4 E 17 46 13 5
Data wykonania otworu	05.09.2011
Godzina wykonania otworu	14:00
Głębokość otworu	2,0 m ppt
Pobór próby	
Data poboru	05.09.2011
Godzina poboru	19:10
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* - zaznaczyć

INSTYTUT NAFTY I GAZU

Monitoring powietrza glebowego

Protokół nr 12/2579/SN

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	E	17	46	05	7				
Data wykonania otworu	05.09.2011								
Godzina wykonania otworu	14:15								
Głębokość otworu	2,0 m ppt								
Pobór próby									
Data poboru	05.09.2011								
Godzina poboru	15:00								
Głębokość poboru próby (zakres)	1,0 – 2,0 m ppt								
Rodzaj pojemnika*	**worek tedlarowy 1dm^3** worek tedlarowy 2 dm^3 pipeta szklana „SUPELCO” pipeta szklana „GLIWICE”								

* - zaznaczyć

Monitoring powietrza glebowego

Protokół nr 13/2579/SN

<table>
<tr><td>Nr punktu pomiarowego</td><td colspan="9">23</td></tr>
<tr><td rowspan="2">Współrzędne punktu</td><td>N</td><td>54</td><td>38</td><td>13</td><td>6</td><td></td><td></td><td></td><td></td></tr>
<tr><td>E</td><td>17</td><td>46</td><td>11</td><td>8</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Data wykonania otworu</td><td colspan="9">06.09.2011</td></tr>
<tr><td>Godzina wykonania otworu</td><td colspan="9">9:30</td></tr>
<tr><td>Głębokość otworu</td><td colspan="9">2 m ppt</td></tr>
<tr><td colspan="10">Pobór próby</td></tr>
<tr><td>Data poboru</td><td colspan="9">06.09.2011</td></tr>
<tr><td>Godzina poboru</td><td colspan="9">17:00</td></tr>
<tr><td>Głębokość poboru próby (zakres)</td><td colspan="9">1,0 – 2,0 m ppt</td></tr>
<tr><td>Rodzaj pojemnika*</td><td colspan="9">worek tedlarowy 1dm^3
<u>worek tedlarowy 2 dm^3</u>
pipeta szklana „SUPELCO”
pipeta szklana „GLIWICE”</td></tr>
</table>

* - zaznaczyć

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Monitoring powietrza glebowego

Protokół nr 14/2579/SN

Nr punktu pomiarowego	24								
Współrzędne punktu	N	54	38	12	9				
	E	17	46	16	8				
Data wykonania otworu	06.09.2011								
Godzina wykonania otworu	9:45								
Głębokość otworu	2 m ppt								
Pobór próby									
Data poboru	06.09.2011								
Godzina poboru	17:10								
Głębokość poboru próby (zakres)	1,0 – 2,0 m ppt								
Rodzaj pojemnika*	worek tedlarowy 1dm^3 **<u>worek tedlarowy 2 dm^3</u>** pipeta szklana „SUPELCO” pipeta szklana „GLIWICE”								

* - zaznaczyć

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Monitoring powietrza glebowego

Protokół nr 15/2579/SN

Nr punktu pomiarowego	22								
Współrzędne punktu	N	54	38	14	8				
	E	17	46	06	3				
Data wykonania otworu	06.09.2011								
Godzina wykonania otworu	9:15								
Głębokość otworu	2,0 m ppt								

Pobór próby	
Data poboru	06.09.2011
Godzina poboru	17:20
Głębokość poboru próby (zakres)	1,0 – 2,0 m ppt
Rodzaj pojemnika*	worek tedlarowy 1dm^3 **worek tedlarowy 2 dm^3** pipeta szklana „SUPELCO” pipeta szklana „GLIWICE”

* - zaznaczyć

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Monitoring powietrza glebowego

Protokół nr 16/2579/SN

Nr punktu pomiarowego	21								
Współrzędne punktu	N	54	38	15	7				
	E	17	46	01	5				
Data wykonania otworu	06.09.2011								
Godzina wykonania otworu	10:00								
Głębokość otworu	2,0 m ptt								
Pobór próby									
Data poboru	06.09.2011								
Godzina poboru	17:30								
Głębokość poboru próby (zakres)	1,0 – 2,0 m ppt								
Rodzaj pojemnika*	worek tedlarowy 1dm^3 **worek tedlarowy 2 dm^3** pipeta szklana „SUPELCO” pipeta szklana „GLIWICE”								

* - zaznaczyć

Monitoring powietrza glebowego

Protokół nr 17/2579/SN

Nr punktu pomiarowego	26								
Współrzędne punktu	N	54	38	12	9				
	E	17	46	00	5				
Data wykonania otworu	06.09.2011								
Godzina wykonania otworu	10:15								
Głębokość otworu	2,0 m ppt								
Pobór próby									
Data poboru	06.09.2011								
Godzina poboru	17:40								
Głębokość poboru próby (zakres)	1,0 – 2,0 m ppt								
Rodzaj pojemnika*	worek tedlarowy 1dm^3 **worek tedlarowy 2 dm^3** pipeta szklana „SUPELCO” pipeta szklana „GLIWICE”								

* - zaznaczyć

Monitoring powietrza glebowego

Protokół nr 18/2579/SN

Nr punktu pomiarowego	25
Współrzędne punktu	N 54 38 14 0 E 17 45 55 4
Data wykonania otworu	06.09.2011
Godzina wykonania otworu	10:30
Głębokość otworu	2,0 m ppt
Pobór próby	
Data poboru	06.09.2011
Godzina poboru	18:10
Głębokość poboru próby (zakres)	1,0 – 2,0 m ppt
Rodzaj pojemnika*	worek tedlarowy 1dm^3 **worek tedlarowy 2 dm^3** pipeta szklana „SUPELCO” pipeta szklana „GLIWICE”

* - zaznaczyć

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Monitoring powietrza glebowego

Protokół nr 19/2579/SN

Nr punktu pomiarowego	20
Współrzędne punktu	N 54 38 16 8 E 17 45 56 2
Data wykonania otworu	06.09.2011
Godzina wykonania otworu	10:45
Głębokość otworu	2,0 m ppt
Pobór próby	
Data poboru	06.09.2011
Godzina poboru	18:20
Głębokość poboru próby (zakres)	1,0 – 2,0 m ppt
Rodzaj pojemnika*	worek tedlarowy 1dm^3 **worek tedlarowy 2 dm^3** pipeta szklana „SUPELCO” pipeta szklana „GLIWICE”

* - zaznaczyć

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Monitoring powietrza glebowego

Protokół nr 20/2579/SN

Nr punktu pomiarowego	15
Współrzędne punktu	N 54 38 17 1 E 17 46 12 3
Data wykonania otworu	06.09.2011
Godzina wykonania otworu	11:00
Głębokość otworu	2,0 m ppt
Pobór próby	
Data poboru	06.09.2011
Godzina poboru	18:30
Głębokość poboru próby (zakres)	1,0 – 2,0 m ppt
Rodzaj pojemnika*	worek tedlarowy 1dm^3 **worek tedlarowy 2 dm^3** pipeta szklana „SUPELCO” pipeta szklana „GLIWICE”

* - zaznaczyć

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Monitoring powietrza glebowego

Protokół nr 21/2579/SN

Nr punktu pomiarowego	9								
Współrzędne punktu	N	54	38	20	4				
	E	17	46	20	2				
Data wykonania otworu	06.09.2011								
Godzina wykonania otworu	11:15								
Głębokość otworu	2,0 m ppt								
Pobór próby									
Data poboru	06.09.2011								
Godzina poboru	18:40								
Głębokość poboru próby (zakres)	1,0 -2,0 m ppt								
Rodzaj pojemnika*	worek tedlarowy 1dm^3 **worek tedlarowy 2 dm^3** pipeta szklana „SUPELCO” pipeta szklana „GLIWICE”								

* - zaznaczyć

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Monitoring powietrza glebowego

Protokół nr 22/2579/SN

Nr punktu pomiarowego	4								
Współrzędne punktu	N	54	38	22	5				
	E	17	46	22	9				
Data wykonania otworu	06.09.2011								
Godzina wykonania otworu	11:30								
Głębokość otworu	2,0 m ppt								
Pobór próby									
Data poboru	07.09.2011								
Godzina poboru	11:15								
Głębokość poboru próby (zakres)	1,0 -2,0 m ppt								
Rodzaj pojemnika*	worek tedlarowy 1dm^3 **worek tedlarowy 2 dm^3** pipeta szklana „SUPELCO” pipeta szklana „GLIWICE”								

* - zaznaczyć

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Monitoring powietrza glebowego

Protokół nr 23/2579/SN

Nr punktu pomiarowego	5								
Współrzędne punktu	N	54	38	21	3				
	E	17	45	28	0				
Data wykonania otworu	06.09.2011								
Godzina wykonania otworu	11:45								
Głębokość otworu	2,0 m ppt								
Pobór próby									
Data poboru	07.09.2011								
Godzina poboru	11:30								
Głębokość poboru próby (zakres)	1,0 – 2,0 m ppt								
Rodzaj pojemnika*	worek tedlarowy 1dm^3 **worek tedlarowy 2 dm^3** pipeta szklana „SUPELCO” pipeta szklana „GLIWICE”								

* - zaznaczyć

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Monitoring powietrza glebowego

Protokół nr 24/2579/SN

<table>
<tr><td>Nr punktu pomiarowego</td><td colspan="9">10</td></tr>
<tr><td rowspan="2">Współrzędne punktu</td><td>N</td><td>54</td><td>38</td><td>18</td><td>7</td><td></td><td></td><td></td><td></td></tr>
<tr><td>E</td><td>17</td><td>46</td><td>24</td><td>5</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Data wykonania otworu</td><td colspan="9">06.09.2011</td></tr>
<tr><td>Godzina wykonania otworu</td><td colspan="9">12:00</td></tr>
<tr><td>Głębokość otworu</td><td colspan="9">2,0 m ppt</td></tr>
<tr><td colspan="10">Pobór próby</td></tr>
<tr><td>Data poboru</td><td colspan="9">07.09.2011</td></tr>
<tr><td>Godzina poboru</td><td colspan="9">11:45</td></tr>
<tr><td>Głębokość poboru próby (zakres)</td><td colspan="9">1,0 – 2,0 m ppt</td></tr>
<tr><td>Rodzaj pojemnika*</td><td colspan="9">worek tedlarowy 1dm^3
<u>worek tedlarowy 2 dm^3</u>
pipeta szklana „SUPELCO”
pipeta szklana „GLIWICE”</td></tr>
</table>

* - zaznaczyć

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Monitoring powietrza glebowego

Protokół nr 25/2579/SN

Nr punktu pomiarowego	16									
Współrzędne punktu	N	54	38	16	0					
	E	17	46	20	1					
Data wykonania otworu	06.09.2011									
Godzina wykonania otworu	12:15									
Głębokość otworu	2,0 m ppt									
Pobór próby										
Data poboru	07.09.2011									
Godzina poboru	12:00									
Głębokość poboru próby (zakres)	1,0 – 2,0 m ptt									
Rodzaj pojemnika*	worek tedlarowy 1dm^3 **<u>worek tedlarowy 2 dm^3</u>** pipeta szklana „SUPELCO” pipeta szklana „GLIWICE”									

* - zaznaczyć

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Monitoring powietrza glebowego

Protokół nr 26/2579/SN

Nr punktu pomiarowego	3
Współrzędne punktu	N 54 38 24 6 E 17 46 16 6
Data wykonania otworu	06.09.2011
Godzina wykonania otworu	12:30
Głębokość otworu	2,0 m ppt
Pobór próby	
Data poboru	07.09.2011
Godzina poboru	12:20
Głębokość poboru próby (zakres)	1,0 – 2,0 m ppt
Rodzaj pojemnika*	worek tedlarowy 1dm^3 **<u>worek tedlarowy 2 dm^3</u>** pipeta szklana „SUPELCO” pipeta szklana „GLIWICE”

* - zaznaczyć

Monitoring powietrza glebowego

Protokół nr 27/2579/SN

Nr punktu pomiarowego	2
Współrzędne punktu	N | 54 | 38 | 26 | 3 E | 17 | 46 | 11 | 4
Data wykonania otworu	06.09.2011
Godzina wykonania otworu	12:45
Głębokość otworu	2,0 m ppt
Pobór próby	
Data poboru	07.09.2011
Godzina poboru	12:30
Głębokość poboru próby (zakres)	1,0 – 2,0 m ppt
Rodzaj pojemnika*	worek tedlarowy 1dm^3 **worek tedlarowy 2 dm^3** pipeta szklana „SUPELCO” pipeta szklana „GLIWICE”

* - zaznaczyć

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Monitoring powietrza glebowego

Protokół nr 28/2579/SN

Nr punktu pomiarowego	1								
Współrzędne punktu	N	54	38	27	7				
	E	17	46	06	5				
Data wykonania otworu	06.09.2011								
Godzina wykonania otworu	13:00								
Głębokość otworu	2,0 m ppt								
Pobór próby									
Data poboru	07.09.2011								
Godzina poboru	12:40								
Głębokość poboru próby (zakres)	1,0 – 2,0 m ppt								
Rodzaj pojemnika*	worek tedlarowy 1dm^3 **worek tedlarowy 2 dm^3** pipeta szklana „SUPELCO” pipeta szklana „GLIWICE”								

* - zaznaczyć

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Monitoring powietrza glebowego

Protokół nr 29/2579/SN

Nr punktu pomiarowego	6								
Współrzędne punktu	N	54	38	24	9				
	E	17	46	05	3				
Data wykonania otworu	06.09.2011								
Godzina wykonania otworu	13:15								
Głębokość otworu	2,0 m ppt								
Pobór próby									
Data poboru	07.09.2011								
Godzina poboru	13:00								
Głębokość poboru próby (zakres)	1,0 – 2,0 m ppt								
Rodzaj pojemnika*	worek tedlarowy 1dm^3 **worek tedlarowy 2 dm^3** pipeta szklana „SUPELCO” pipeta szklana „GLIWICE”								

* - zaznaczyć

Monitoring powietrza glebowego

Protokół nr 30/2579/SN

Nr punktu pomiarowego	7
Współrzędne punktu	N 54 38 24 1 E 17 46 10 9
Data wykonania otworu	06.09.2011
Godzina wykonania otworu	13:30
Głębokość otworu	2,0 m ppt
Pobór próby	
Data poboru	07.09.2011
Godzina poboru	13:10
Głębokość poboru próby (zakres)	1,0 – 2,0 m ppt
Rodzaj pojemnika*	worek tedlarowy 1dm^3 **worek tedlarowy 2 dm^3** pipeta szklana „SUPELCO” pipeta szklana „GLIWICE”

* - zaznaczyć

INSTYTUT NAFTY I GAZU

Monitoring powietrza glebowego

Protokół nr 31/2579/SN

Nr punktu pomiarowego	8								
Współrzędne punktu	N	54	38	22	0				
	E	17	46	15	5				
Data wykonania otworu	07.09.2011								
Godzina wykonania otworu	9:30								
Głębokość otworu	2,0 m ppt								
Pobór próby									
Data poboru	07.09.2011								
Godzina poboru	17:45								
Głębokość poboru próby (zakres)	1,0 – 2,0 m ppt								
Rodzaj pojemnika*	worek tedlarowy 1dm^3 **worek tedlarowy 2 dm^3** pipeta szklana „SUPELCO” pipeta szklana „GLIWICE”								

* - zaznaczyć

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Monitoring powietrza glebowego

Protokół nr 32/2579/SN

Nr punktu pomiarowego	11
Współrzędne punktu	N 54 38 22 2 E 17 46 01 3
Data wykonania otworu	07.09.2011
Godzina wykonania otworu	10:00
Głębokość otworu	1,9 m ppt
Pobór próby	
Data poboru	07.09.2011
Godzina poboru	18:10
Głębokość poboru próby (zakres)	1,0 – 2,0 m ppt
Rodzaj pojemnika*	worek tedlarowy 1dm^3 **worek tedlarowy 2 dm^3** pipeta szklana „SUPELCO” pipeta szklana „GLIWICE”

* - zaznaczyć

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Monitoring powietrza glebowego

Protokół nr 33/2579/SN

Nr punktu pomiarowego	12								
Współrzędne punktu	N	54	38	21	4				
	E	17	46	07	7				
Data wykonania otworu	07.09.2011								
Godzina wykonania otworu	10:15								
Głębokość otworu	2,0 m ppt								
Pobór próby									
Data poboru	07.09.2011								
Godzina poboru	18:20								
Głębokość poboru próby (zakres)	1,0 – 2,0 m ppt								
Rodzaj pojemnika*	worek tedlarowy 1dm^3 **worek tedlarowy 2 dm^3** pipeta szklana „SUPELCO” pipeta szklana „GLIWICE”								

* - zaznaczyć

Monitoring powietrza glebowego

Protokół nr 34/2579/SN

Nr punktu pomiarowego	42
Współrzędne punktu	N 54 38 20 1 E 17 45 58 5
Data wykonania otworu	07.09.2011
Godzina wykonania otworu	11:00
Głębokość otworu	2,0 m ppt
Pobór próby	
Data poboru	07.09.2011
Godzina poboru	18:35
Głębokość poboru próby (zakres)	1,0 – 2,0 m ppt
Rodzaj pojemnika*	worek tedlarowy 1dm^3 **<u>worek tedlarowy 2 dm^3</u>** pipeta szklana „SUPELCO” pipeta szklana „GLIWICE”

* - zaznaczyć

INSTYTUT NAFTY I GAZU

Monitoring powietrza glebowego

Protokół nr 35/2579/SN

Nr punktu pomiarowego	51
Współrzędne punktu	N 54 38 19 6 E 17 46 13 2
Data wykonania otworu	12.09.2011
Godzina wykonania otworu	11:10
Głębokość otworu	1,5 m ppt
Pobór próby	
Data poboru	12.09.2011
Godzina poboru	18:10
Głębokość poboru próby (zakres)	1,0 – 1,5 m ppt
Rodzaj pojemnika*	**worek tedlarowy 1dm^3** worek tedlarowy 2 dm^3 pipeta szklana „SUPELCO” pipeta szklana „GLIWICE”

* - zaznaczyć

INSTYTUT NAFTY I GAZU

Monitoring powietrza glebowego

Protokół nr 36/2579/SN

Nr punktu pomiarowego	52
Współrzędne punktu	N 54 38 18 2 E 17 46 15 3
Data wykonania otworu	12.09.2011
Godzina wykonania otworu	11:30
Głębokość otworu	1,8 m ppt
Pobór próby	
Data poboru	12.09.2011
Godzina poboru	18:40
Głębokość poboru próby (zakres)	1,0 – 1,8 m ppt
Rodzaj pojemnika*	**<u>worek tedlarowy 1dm^3</u>** worek tedlarowy 2 dm^3 pipeta szklana „SUPELCO” pipeta szklana „GLIWICE”

* - zaznaczyć

INSTYTUT NAFTY I GAZU

Monitoring powietrza glebowego

Protokół nr 37/2579/SN

Nr punktu pomiarowego	53
Współrzędne punktu	N 54 38 17 1 E 17 46 12 3
Data wykonania otworu	12.09.2011
Godzina wykonania otworu	11:50
Głębokość otworu	1,5 m ppt
Pobór próby	
Data poboru	12.09.2011
Godzina poboru	18:50
Głębokość poboru próby (zakres)	1,0 – 1,5 m ppt
Rodzaj pojemnika*	**worek tedlarowy 1dm^3** worek tedlarowy 2 dm^3 pipeta szklana „SUPELCO” pipeta szklana „GLIWICE”

* - zaznaczyć

Monitoring powietrza glebowego

Protokół nr 38/2579/SN

Nr punktu pomiarowego	30
Współrzędne punktu	N 54 38 16 4 E 17 46 09 6
Data wykonania otworu	12.09.2011
Godzina wykonania otworu	12:00
Głębokość otworu	2,5 m ppt
Pobór próby	
Data poboru	12.09.2011
Godzina poboru	19:00
Głębokość poboru próby (zakres)	1,0 – 1,8 m ppt
Rodzaj pojemnika*	**worek tedlarowy 1dm^3** worek tedlarowy 2 dm^3 pipeta szklana „SUPELCO” pipeta szklana „GLIWICE”

* - zaznaczyć

INSTYTUT NAFTY I GAZU

Monitoring powietrza glebowego

Protokół nr 39/2579/SN

Nr punktu pomiarowego	54									
Współrzędne punktu	N	54	38	15	4					
	E	17	46	08	8					
Data wykonania otworu	12.09.2011									
Godzina wykonania otworu	12:20									
Głębokość otworu	1,7 m ppt									
Pobór próby										
Data poboru	12.09.2011									
Godzina poboru	19:10									
Głębokość poboru próby (zakres)	1,0 – 1,7 m ppt									
Rodzaj pojemnika*	**worek tedlarowy 1dm^3** worek tedlarowy 2 dm^3 pipeta szklana „SUPELCO” pipeta szklana „GLIWICE”									

* - zaznaczyć

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Monitoring powietrza glebowego

Protokół nr 40/2579/SN

Nr punktu pomiarowego	55								
Współrzędne punktu	N	54	38	14	9				
	E	17	46	11	5				
Data wykonania otworu	12.09.2011								
Godzina wykonania otworu	13:00								
Głębokość otworu	1,8 m ppt								
Pobór próby									
Data poboru	12.09.2011								
Godzina poboru	19:20								
Głębokość poboru próby (zakres)	1,0 – 1,8 m ppt								
Rodzaj pojemnika*	**worek tedlarowy 1dm^3** worek tedlarowy 2 dm^3 pipeta szklana „SUPELCO” pipeta szklana „GLIWICE”								

* - zaznaczyć

II. Laboratory works

II.1 Laboratory work methods

Forty Tedlar bags with soil air samples and 2 steel pipettes with shale gas from the Łebień LE-2H well were sent to the Oil and Gas Institute Laboratory for analyses. The analyses comprised molecular and isotopic composition of both soil air and shale gas samples.

II.1.1. Molecular composition

Chromatographic analyses made it possible to determine concentrations of:
O_2, N_2, CO, CO_2, C_1, C_2, C_3, iC_4 and nC_4 in soil air
and O_2, N_2, CO, CO_2, C_1, C_2, C_3, iC_4, nC_4, iC_5, nC5, $neoC_5$ and sum of hydrocarbons C_6, C_7, C_8 and C_9 in shale gas samples. Analyses of GC were made using AGILENT 7890A gas chromatograph with ChemStation software and a system of columns and detectors:

- TCD and FID1 detectors - HP-PLOT/Q and HP-MOLESIEVE 5A capillary columns
- FID 2 detector – HP-PONA capillary column

II.1.2. Isotopic composition

Isotopic composition of coal and hydrogen was determined using GC-IRMS (Isotope Ratio Mass Spectrometer) Delta V Advantage mass spectrometer. Samples were prepared “on-line” thanks to integrated TRACE GC ULTRA gas chromatograph of Thermo Electron Corporation and mass spectrometer. Separation of gas components took place in HP-PLOT/Q capillary column.

Fig. II.1. Delta V Advantage mass spectrometer integrated with Flash 2000 elementary analyser and Trace GC Ultra gas chromatographic

Fig. II.2. Delta V Advantage mass spectrometer

II.2. Results of analyses of soil air

Molecular composition of soil air is shown in Tables II.1 to II.4. Concentrations of components were counted over to 100% of gas and the obtained results are given in units [ppm]. In analysis of isotopic composition it was possible to determine $\delta^{13}C$ in carbon dioxide (with a few exceptions, because of too small amount of gas for analysis or too low concentration of $C0_2$). Isotopic composition of methane could not be analysed because of too low concentrations of that gas (below the limit of detection for analyses of isotopic composition). Table II.5 shows the obtained results.

Table II.1. Molecular composition of soil gases sampled at the Points no. 1, 2, 3, 4, 5, 6, 7, 8, 9 and 10 [ppm]
the original TABLE is given

	Punkt nr 1/1	Punkt nr 2/1	Punkt nr 3/1	Punkt nr 4/1	Punkt nr 5/1	Punkt nr 6/1	Punkt nr 7/1	Punkt nr 8/1	Punkt nr 9/1	Punkt nr 10/1
O_2	208 057,5	186 243,3	208 956,1	69 605,5	204 909,1	167 834,9	180 410,5	174 350,7	206 087,2	192 337,2
N_2	789 925,0	797 136,6	789 103,0	856 413,4	788 872,5	795 423,5	796 406,6	800 516,7	789 653,4	792 159,2
CO_2	2 010,6	16 609,0	1 933,5	73 965,6	6 214,3	36 733,6	23 175,2	25 116,6	4 253,3	15 494,4
CO	3,0	4,1	3,4	4,7	2,7	2,9	3,1	5,2	1,9	3,2
C_1	3,8	5,9	4,0	9,1	1,5	5,2	4,6	9,1	4,2	5,1
C_2	0,0	1,0	0,0	1,7	0,0	0,0	0,0	1,6	0,0	0,9
C_3	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
i-C_4	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
n-C_4	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0

Table II.2. Molecular composition of soil gases sampled
at the Points no. 11, 12, 15, 16, 20, 21, 22, 23, 24 and 25 [ppm]
the original TABLE is given

	Punkt nr 11/1	Punkt nr 12/1	Punkt nr 15/1	Punkt nr 16/1	Punkt nr 20/1	Punkt nr 21/1	Punkt nr 22/1	Punkt nr 23/1	Punkt nr 24/1	Punkt nr 25/1
O_2	173 507,2	210 349,5	206 407,7	187 805,2	189 368,1	206 230,2	169 713,4	168 163,8	205 643,2	209 147,6
N_2	793 215,7	788 982,8	791 239,0	793 644,4	788 335,3	790 243,0	778 879,2	799 218,7	787 892,1	788 998,9
CO_2	33 274,1	662,9	2 344,4	18 548,4	22 288,5	3 518,2	51 402,5	32 609,7	6 461,0	1 848,4
CO	1,8	2,5	3,6	1,9	3,3	3,6	2,6	4,0	2,2	2,4
C_1	1,2	2,3	5,4	0,0	4,8	5,1	2,3	3,9	1,6	2,7
C_2	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
C_3	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
i-C_4	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
n-C_4	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0

Table II.3. Molecular composition of soil gases sampled at the Points no. 26, 27, 28, 29, 30, 31, 33, 34, 35 and 37 [ppm]

the original TABLE is given

	Punkt nr 26/1	Punkt nr 27/1	Punkt nr 28/2	Punkt nr 29/1	Punkt nr 30/1	Punkt nr 31/2	Punkt nr 33/1	Punkt nr 34/2	Punkt nr 35/1	Punkt nr 37/2
O_2	205 964,2	200 341,2	207 578,6	204 766,0	204 898,7	152 374,8	204 680,6	198 587,7	208 727,9	178 642,4
N_2	790 341,6	792 817,7	784 717,2	789 958,8	792 012,6	759 567,7	788 113,8	760 143,1	788 797,2	785 370,4
CO_2	3 686,8	6 819,3	7 698,7	5 270,5	3 084,9	87 742,3	7 200,9	41 256,7	2 055,4	35 974,3
CO	3,3	5,4	2,0	2,5	2,4	6,5	2,3	5,3	2,7	4,4
C_1	4,1	13,8	3,6	2,2	1,4	308,6	2,5	7,2	416,9	8,6
C_2	0,0	2,6	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
C_3	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
i-C_4	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
n-C_4	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0

Table II.4. Molecular composition of soil gases sampled at the Points no. 38, 39, 40, 41, 42, 51, 52, 53, 54 and 55 in [ppm]

the original TABLE is given

	Punkt nr 38/1	Punkt nr 39/1	Punkt nr 40/1	Punkt nr 41/1	Punkt nr 42/1	Punkt nr 51/1	Punkt nr 52/1	Punkt nr 53/1	Punkt nr 54/1	Punkt nr 55/1
O_2	167 198,8	205 829,6	191 977,8	115 119,6	199 936,1	195 753,5	207 085,9	207 445,3	209 777,1	176 668,0
N_2	793 067,5	789 493,0	787 126,4	837 685,7	789 690,2	796 137,5	789 899,7	789 895,6	788 657,7	786 571,4
CO_2	39 393,5	4 669,1	20 890,4	47 178,0	10 371,6	8 084,4	2 872,9	2 648,6	1 560,8	36 756,0
CO	3,6	3,4	2,8	5,2	2,2	6,8	3,1	4,4	2,3	3,0
C_1	336,6	4,8	2,6	9,7	0,0	15,4	138,4	6,1	2,2	1,6
C_2	0,0	0,0	0,0	1,8	0,0	2,4	0,0	0,0	0,0	0,0
C_3	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
i-C_4	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
n-C_4	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0

Table II.5. Isotopic composition of carbon $\delta^{13}C$ in soil air [‰ vs PDB]
the original TABLE is given

	$\delta^{13}C$ [‰]		$\delta^{13}C$ [‰]		$\Delta^{13}C$ [‰]		$\Delta^{13}C$ [‰]
Punkt nr 1	-22,0	Punkt nr 11	-24,1	Punkt nr 26	-21,5	Punkt nr 38	-21,8
Punkt nr 2	-23,9	Punkt nr 12	-14,5	Punkt nr 27	-22,2	Punkt nr 39	-23,1
Punkt nr 3	-21,1	Punkt nr 15	-18,4	Punkt nr 28	ns	Punkt nr 40	-20,9
Punkt nr 4	-25,8	Punkt nr 16	-22,9	Punkt nr 29	ns	Punkt nr 41	-23,3
Punkt nr 5	-21,9	Punkt nr 20	-23,8	Punkt nr 30	-11,7	Punkt nr 42	-22,4
Punkt nr 6	-24,1	Punkt nr 21	-23,4	Punkt nr 31	ns	Punkt nr 51	-20,7
Punkt nr 7	-24,7	Punkt nr 22	-23,1	Punkt nr 33	-20,1	Punkt nr 52	-20,4
Punkt nr 8	-23,7	Punkt nr 23	ns	Punkt nr 34	ns	Punkt nr 53	-18,7
Punkt nr 9	-23,0	Punkt nr 24	-24,5	Punkt nr 35	-21,7	Punkt nr 54	-17,0
Punkt nr 10	-23,0	Punkt nr 25	ns	Punkt nr 37	ns	Punkt nr 55	-22,4

ns – measurements not possible because of too small amount of gas for analysis or too low concentration of CO_2

II.3. Results of analyses of shale gas from the Łebień LE-2H well

Samples of shale gas from the Łebień LE-2H well were taken twice, on 12 and 16 September 2011, after completion of fracturing treatments. Table II.6 shows isotopic composition of both carbon and hydrogen for individual components of shale gas. Concentrations of carbon dioxide in shale gas were so low that it appeared not possible to determine $\delta^{13}C$.

Table II.6. Isotopic composition of carbon $\delta^{13}C$ [‰ vs PDB] and hydrogen δD [‰ vs VSMOW] in individual components of shale gas samples taken from the Łebień LE-2H well on 12 and 26 September 2011

the original TABLE is given

	gaz z odwiertu Łebień 12.09.2011	gaz z odwiertu Łebień 26.09.2011
$\delta^{13}CO_2$	ns	ns
$\delta^{13}C_1$	-42,6	-42,2
$\delta^{13}C_2$	-33,9	-33,9
$\delta^{13}C_3$	-28,3	-28,1
$\delta^{13}n\text{-}C_4$	-26,7	-27,0
$\delta^{13}n\text{-}C_5$	-26,6	-26,5
$\delta D\ CH_4$	-149,3	-152,2

ns – measurements not possible because of too small amount of component for analysis

Annex

to the final report "Studies of hydrocarbon background in soil gas and analyses of shale gas for defining parameters making possible explanation of origin of potential occurrences of natural gas outside installation", compiled in accordance with the Agreement No. 603/2011/6

The results of analyses of molecular composition of soil air made it possible to differentiate four groups of samples on the basis of differences in concentration of CO_2 and CH_4 (Fig. 1).

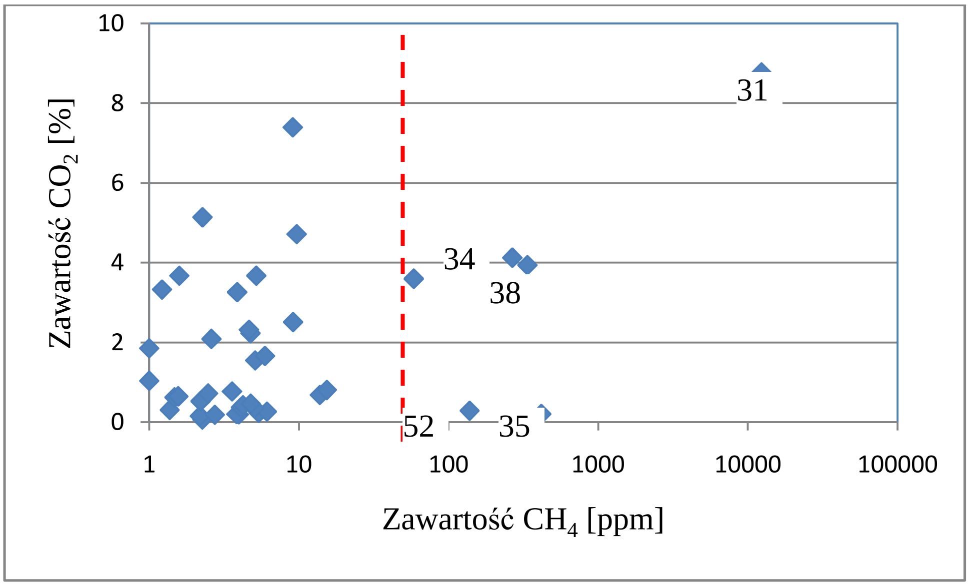

Fig. 1. Concentration of methane in soil air samples from the Łebień LE-2H area in relation to concentration of carbon dioxide

the original FIGURE is given

The first group comprises four samples (samples no. 34, 38, 36 and 52) with methane concentration over 100 ppm and that of CO_2 – up to 4%. The presence of methane in these samples, especially samples no. 34 and 38, is most probably related to their origin. The samples were taken at meadows and in proximity of rivers and floodings and, therefore, the presence of methane and carbon dioxide may be the result of ongoing processes of decay and fermentation of organic matter which lead to production of biogenic gas. Isotopic composition of carbon from carbon dioxide of these samples is about -22 ‰ which may indicate its organic origin.

The sample no. 31 is a single one which is characterized by high concentration of CO_2 and at the same time the highest CH_4 concentration in samples collected before the start of the fracturing treatments on the Łebień LE-2H well. This sample was taken in vicinities of a peatbog which may mean anthropogenic character of the analysed compounds. However, the size of that samples appeared too small to carry out isotopic analyses what made any more precise identification of origin of these gases not possible. The remaining samples were found to yield methane in insignificant concentrations (markedly below 100 ppm) which may be treated as the regional geochemical background values. Samples of the latter group may be differentiated with respect to isotopic composition of carbon in carbon dioxide. It is clearly visible that $\delta^{13}C$ become more negative when concentrations of CO_2 are high. This is related to a lower share of CO_2 of atmospheric origin (with $\delta^{13}C$ equal about -8‰) and higher share of CO_2 from photosynthesis and respiration processes ($\delta^{13}C$ equal about -26‰) (Fig. 2).

Fig. 2. Isotopic composition of carbon at various placed on the Earth and mean annual influence on atmospheric value of $\delta^{13}C$ (after Yakir, 2004).

the original FIGURE is given

Variability in isotopic composition of carbon in carbon dioxide in dependence on its share in soil air is shown in Fig. 3.

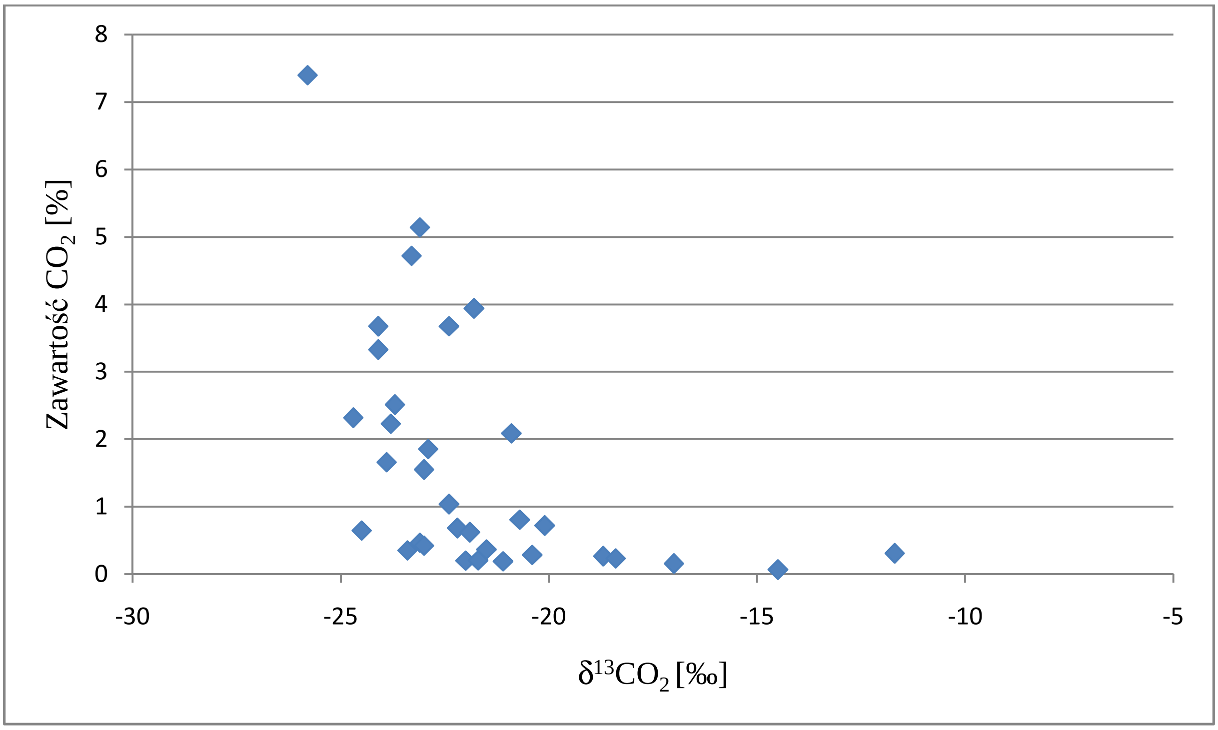

Fig. 3. Isotopic composition of carbon in CO_2 (in ‰) in dependence on CO_2 concentration in soil air (in %)
the original FIGURE is given

Taking into account the major aim of the task, that is assessment of influence of the fracturing treatments performed on the Łebień LE-2H well on concentration of methane in soil air, it should be stated that the studies did not show any increase in concentration of methane in the analysed samples. This means that in that case the technological treatments did not have any discernible influence on composition of soil air. Distributions of concentrations of methane and carbon dioxide in samples taken in accordance with pre-determined network of sampling points are shown in Fig. 4 and 5.

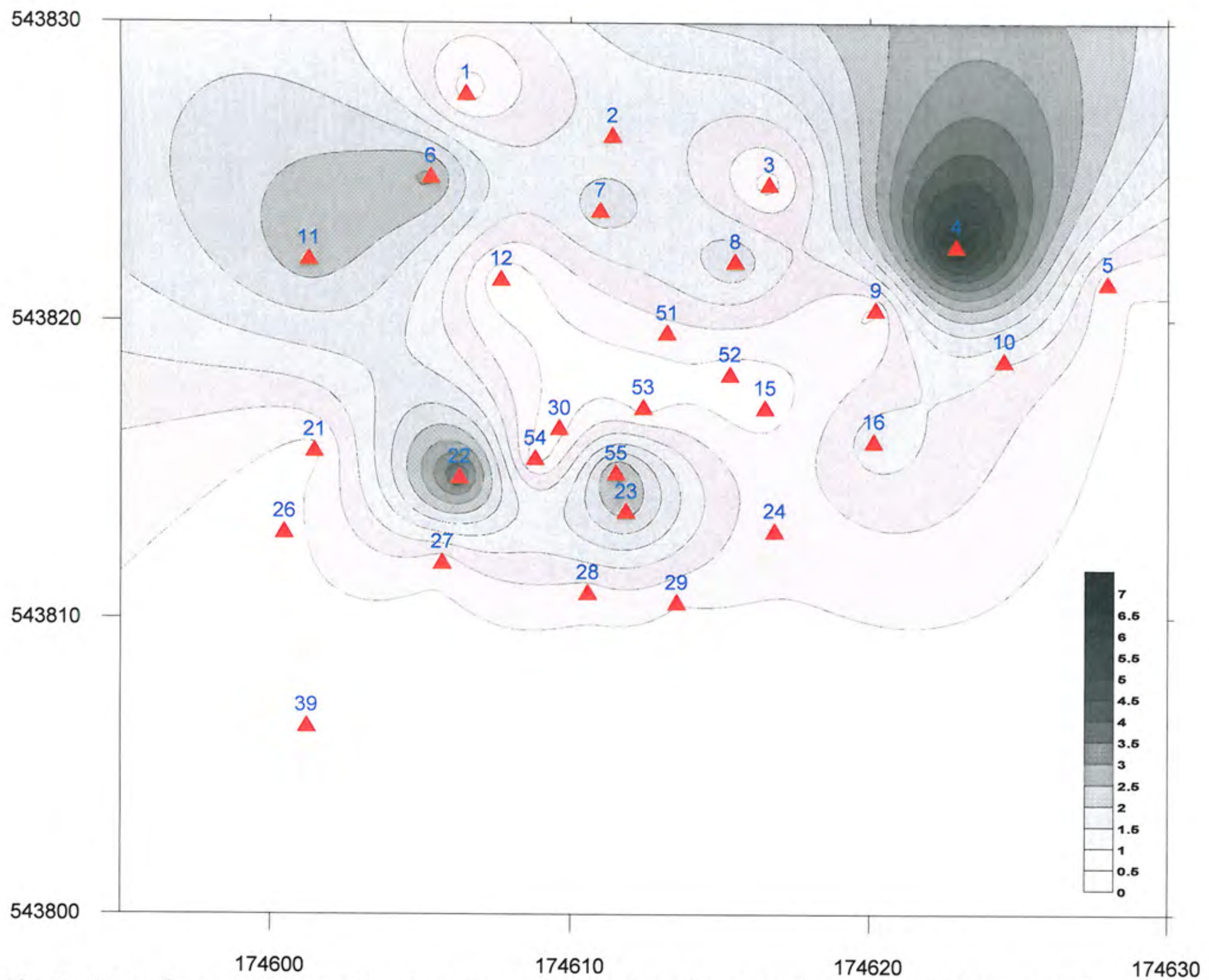

Fig. 4a. Map of concentrations of carbon dioxide in soil air in direct vicinity of the Łebień LE-2H well

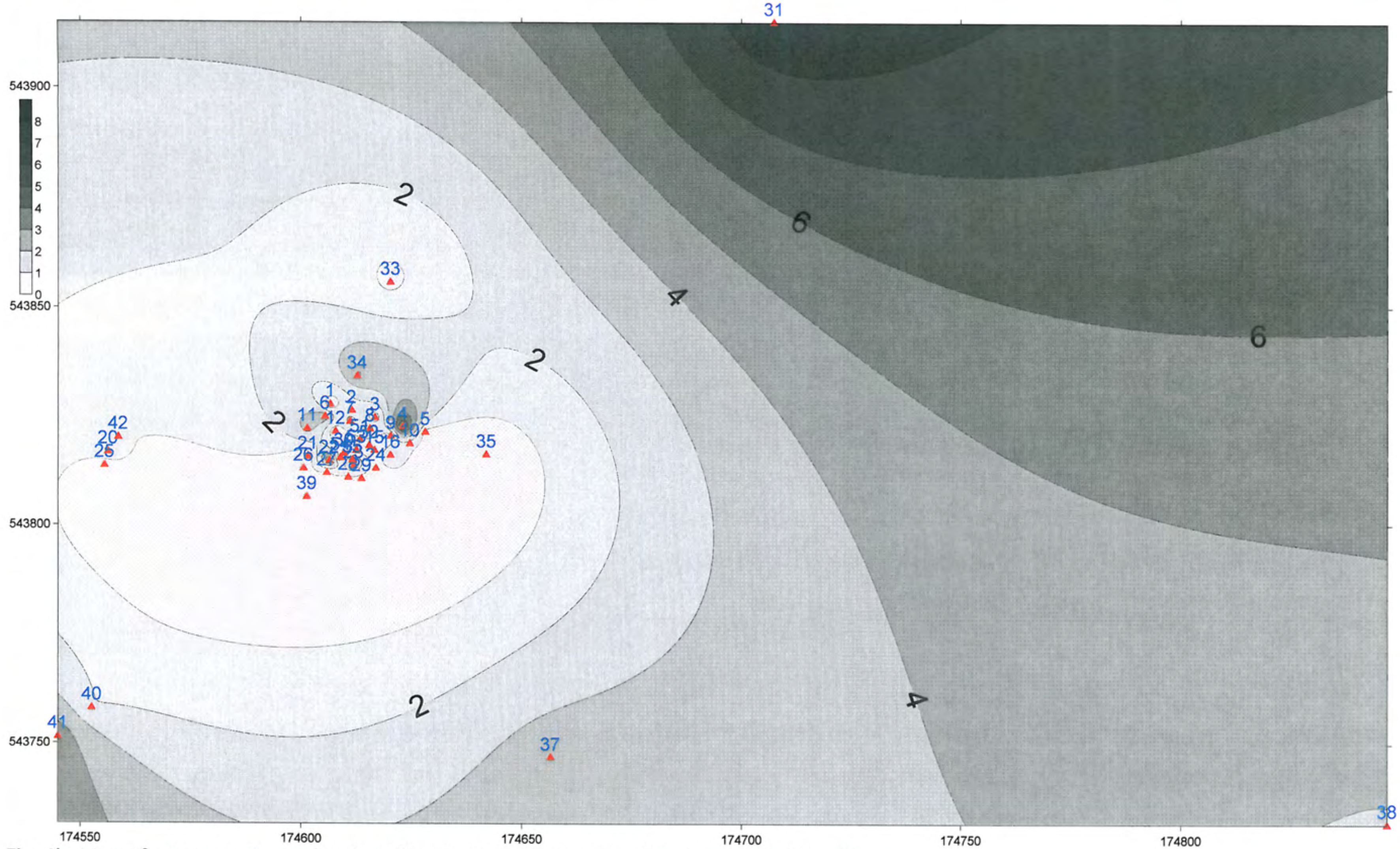

Fig. 4b. Map of concentrations of carbon dioxide in soil air in area of the Łebień LE-2H well

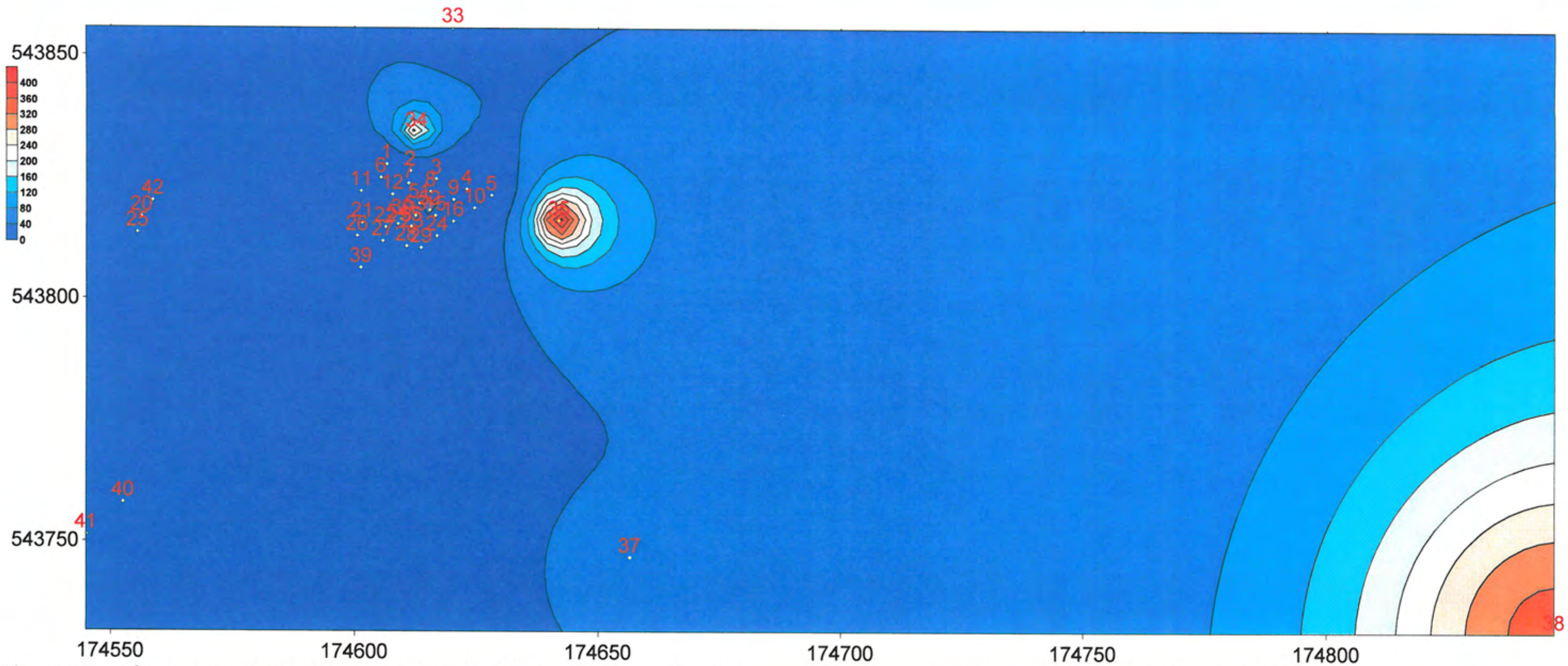

Fig. 5. Map of concentrations of methane in soil air in area of the Łebień LE-2H well (including measurement points in the periphery of that area)

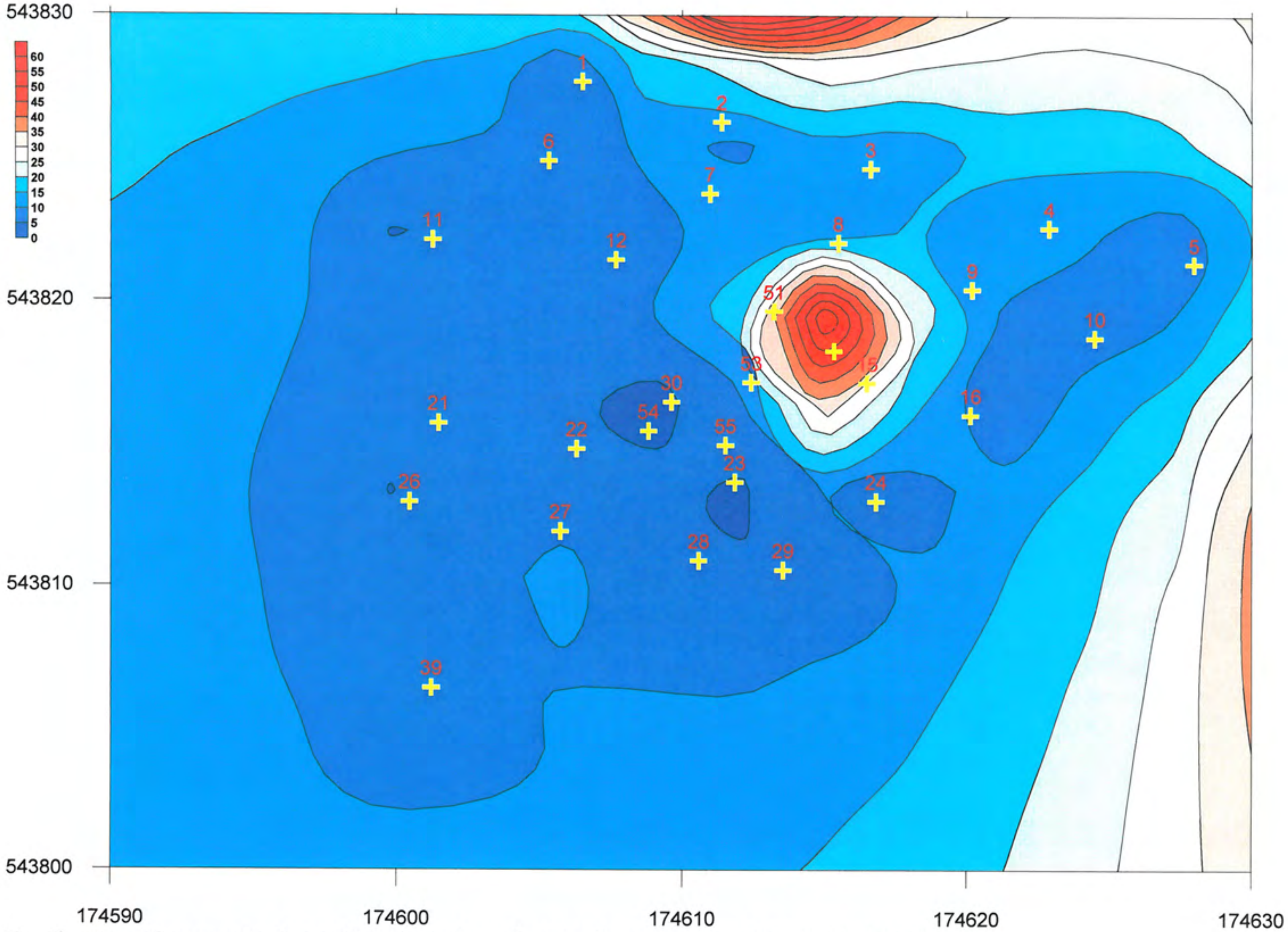

Fig. 5b. Map of concentrations of methane in soil air in direct vicinity of the Łebień LE-2H well

ANNEX 12

Ecotoxicological studies for assessment of ecological risk related to fracturing process

Warsaw University of Technology
Faculty of Environmental Engineering

Ecotoxicological studies for assessment of ecological risk related to fracturing process

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Warsaw, October 2011

Ecotoxicological studies for assessment of ecological risk related to fracturing process

legal basis of the study - Agreement no. 604/2011/G concluded between State Treasury – Ministry of Environment and Biology Division of Faculty of Environmental Engineering of the Warsaw University of Technology on 12 September 2011

1. Introduction

In accordance with general premises, the present study was designed as an element of information packet indispensable for effective management, control and supervision of investments in prospecting, exploration and eventual exploitation of unconventional hydrocarbon resources in Poland. The goals of this study were to conduct ecotoxicological tests of samples of technological fluids used in hydraulic fracturing and flowback technological fluids, especially in the range of acute toxicity, necessary for assessment of ecological risk of failure of installation, uncontrolled spill of liquid contaminant and other accidents which may lead to pollution of water and soil. Assessment of risks connected with use of these technological fluids in exploitation of shale gas resources should give the basis for taking appropriate actions to clean-up (utilize) the fluids.

2. Scope and range of the study

The study was aimed at assessing ecotoxicity of six samples of fluids used in hydraulic fracturing processes:

- 20% HCl with additions of fluids from acid tank, used in the first stage of fracturing;
- fracturing fluid with resin-coated silica sand, diluted with water in proportion 1:1;
- flowback fluid sampled after drilling out the plug 2;
- flowback fluid sampled after drilling out the plug 5/6;
- flowback fluid sampled after nitrogen treatment;
- flowback fluid sampled after nitrogen treatment and before closing the well.

The range of the studies comprised:

- a series of tests including: growth inhibition test with algae Raphidocelis subcapicata, immobilization test with crustacean Daphnia magna, survival test on fish Lebistes reticulatis, test of seed germination and early growth of three species of plants – Sorghum saccharatum, Lepidium sativum and Sinapsis alba;
- determination of values of lethal and effective concentrations - $LC(EC)_{50}$-t;
- estimation of values of acute toxic units Tu_a;
- evaluation of toxic effect of the studied samples on bioindicators with reference to the European Union criteria;
- calculation of safe concentrations (SC) in relation to acute toxicity;
- assessment of ecological risk.

3. Methodology of studies

3.1. Samples for studies

The samples were delivered by the Customer, in accordance with the time table and specifications as given in Table 1.

The studies covered 6 samples: five in the same state as provided and one (sample no. 3, representing double concentrated fracturing fluid with addition of resin-coated silica sand), was diluted with water from the open-air reservoir (sample W) in proportion 1:1 as recommended by the Customer.

Table 1. Types of samples and time table of delivery to the Contractor

No. (symbol) of sample	Type of sample	Sample volume [dcm^3]	Date of delivery of sample to Contractor
1	20% HCl with additions from acid tank, used in the first stage of fracturing	**5**	22-08-2011
W	Water from open-air reservoirs	**5**	
3	Double concentrated fracturing fluid with addition of resin-coated silica sand	**5**	
4	Flowback fluid sampled after drilling out the plug 2	**5**	02-09-2011
7	Flowback fluid sampled after drilling out the plug 5/6	**5**	
12a	Flowback fluid sampled after nitrogen treatment	**5**	12-09-2011
15	Flowback fluid sampled after nitrogen treatment and before closing the well	**5**	19-09-2011

3.2. Ecotoxicity tests

3.2.1. Growth inhibition test on fresh-water algae with the use of unicellular green algae

The studies have been carried in accordance with methodology as given in the norm PN-EN ISO 8692 [1]. The tests were conducted on strain no. CCALA 433. of unicellular green algae *Raphidocella subcapitata (Selenstrum capricornutum).* Several dilutions of the studied samples were made using mineral bed for growing algae. The samples were inoculated with suspension of algae in the logarithmic phase of growth. Concentration of algae cells at the beginning of the test (time 0) was equal 104 cell/ml. Incubation of the samples was carried out in Filotron incubator under constant temperature of 23^{o}C and continuous illumination (8 000 lx) for 72 hours. Subsequently a quantitative analysis was performed using a reversed microscope. The test was replicated three times and values presented here are arithmetic mean of the obtained results.

3.2.2. Immobilization test with Daphnia magna

The studies have been carried in accordance with methodology as given in the norm OECD 202 [2]. The tests were conducted on neonates (organisms less than 24 hours old) of Daphnia magna, coming from cultures raised at the Biology Division of Faculty of Environmental Engineering of the Warsaw University of Technology. The studied samples were diluted several times with water purified by use of biofilter. Ten test organisms were placed in each concentration. The tests were carried out at temperature of 24^{o}C for 48 hours. The percentage immobility of animals at 24 and 48 hours was estimated for each concentration. The animals were not fed during the tests. The tests were replicated three times and values presented here are arithmetic mean of the obtained results.

3.2.3. Acute survival test on guppy fish *Lebistes reticulatis* Peters

The studies have been carried in accordance with methodology as given in the norm PN-90/C-04610 [3]. The tests were conducted on subadult individuals of fish *Lebistes reticulatis* Peters, not showing a sexual dimorphism. The fish were coming from laboratory in-house culture of the Biology Division of Faculty of Environmental Engineering of the Warsaw University of Technology. The studied samples were diluted several times with water purified by use of biofilter. Five test organisms were placed in each concentration. The tests were carried out at temperature of 20^{o}C for 96 hours. The percentage of dead animals at 24 and 48 hours was estimated for each concentration. Dead animals were counted after 24, 48 and 96 hours of exposure in each studied concentration and cumulative percentage mortality was computed. The tests were replicated three times and values presented here are arithmetic mean of the obtained results.

3.2.4. Test of seed germination and early growth of plants – Phytotoxkit ^{TM}

The studies have been carried in accordance with methodology as given in the instructions of producer of the test, MicroBiotests [Belgium] [4]. The test was conducted on selected seeds of three species of plants: monocotyledonous *Sorghum saccharatum* and dicotyledonous *Lepidium sativum* and *Sinapsis alba*, supplied by its producer. The studied samples were diluted several times with distillated water and subsequently used to moisten standard soil placed on test plates. The moistened soil was covered with filter paper on which 10 seeds of the same plant were placed in one line. Test plates were incubated at temperature of 25oC for 3 days. Afterwards, percentage inhibition of seed germination and root growth of roots was calculated. Measurements of length of roots were made using UTHSCSA ImageTool™ (IT) version 3.0 analysis program in digital image processing. The tests were replicated three times and values presented here are arithmetic mean of the obtained results.

3.3. Calculation procedures

3.3.1. Calculation of inhibition of algal growth

Growth rate of algae was calculated from formula:

$$\mu = \frac{\boldsymbol{In}N_n - \boldsymbol{In}N_o}{t_n}$$

where: N_o – number of algae cells in 1 cm^3 in time t_o;
N_n – number of algae cells in 1 cm^3 in time t;
t_n – time ($t - t_o$).

Algal growth inhibition was calculated from formula:

$$I\mu_i = \frac{\mu_c - \mu_i}{\mu_c} \cdot 100$$

where: $I\mu_i$ - percentage inhibition;
μ_i – average growth of algae in the studied concentration;
μ_c – average control sample growth rate.

3.3.2 Calculation of growth inhibition of seeds of higher plants in Phytotoxkit ™ test

Percentage inhibition of germination of seeds and percentage inhibition of growth of roots were calculated from formula:

$$I = \frac{A - B}{A} \cdot 100$$

where: A – average number of germinating seeds or length of roots in control soil;
B – average number of germinating seeds or length of roots in studied sample.

3.3.3. Calculation of lethal and effective concentrations $LC(EC)_{50}$-t

Lethal and effective concentrations [% v/v] were calculated by probit method [5] in accordance with formula:

$$LC(EC)_{50} - t = 10^{\frac{5-\overline{y}+a\cdot\overline{x}}{a}}$$

where: $\overline{x}$ – average value of logarithms for individual concentrations;
a – regression coefficient;
5 – constant value of probit corresponding to 50% mortality / inhibition;
$\overline{y}$ – average value of probits responsible for % of mortality / inhibition for individual concentrations.

3.3.4. Calculation of acute toxic units - TU_a

Acute toxic units TU_a [6] were calculated from formula:

$$TU_a = \frac{100}{LC(EC)_{50}}$$

where:
$LC(EC)_{50}$ – lethal (or effective) concentration determined for each of the performed toxicity tests [% v/v],
100 – the highest concentration of the studied sample [% v/v].

3.3.5. Calculation of safe concentrations (SC)

Safe concentrations [% v/v] were calculated by US EPA method [7, 8) from formula:

$$SC = \frac{CMC}{TU_{a,max}RPMF} \times 100\%$$

where:
CMC – Criteria Maximum Concentration for a given sample in Tu_a, at which organisms can be exposed for a brief period of time (1 hour) without causing an acute effect (CMC = 0.3)
$Tu_{a\ max}$ – the highest of acute toxic values TU_a for a given sample
RPMT - Reasonable Potential Multiplying Factor, multiplier dependent on coefficient of variation, confidence interval and probability

4. Results of studies

4.1. Test studies

- Growth test on algae *Raphidocelis subcapitata*

The studies showed that the sample of 20% HCl with additions of fluids from acid tank, used in the first stage of fracturing, was identified as the most toxic and inhibitory to algae growth.
Its EC_{50}-72h value was 0.05% (see Table 2).

Table 2. Results of ecotoxicity studies on fluid samples from hydraulic fracturing treatments, obtained in growth inhibition test with algae *Raphidocelis subcapicata*

Sample No.	Type of sample	EC_{50}-72h [% v/v] [95% confidence interval]
1	20% HCl with additions from acid tank, used in the first stage of fracturing	0,05 (0,02-0,9)
3+W 1:1	Fracturing fluid with addition of resin-coated silica sand, diluted with water sample (W) from open-air reservoir in proportion 1:1	36,06 (11,26-15,99)
4	Flowback fluid sampled after drilling out the plug 2	13,56 (11,26-15,99)
7	Flowback fluid sampled after drilling out the plug 5/6	87,12 (79,98-94,34)
12a	Flowback fluid sampled after nitrogen treatment	4,18 (3,53-4,78)
15	Flowback fluid sampled after nitrogen treatment and before closing the well	5,46 (4,21-6,66)

The samples of fracturing fluid with addition of silica sand and flowback fluid sampled after drilling out the plugs 2 and 5/6 appeared much less harmful and their EC_{50}-72h values were equal 36.06%, 13.56% and 87.12%, respectively. Flowback fluids sampled after nitrogen treatment were found to be characterized by a higher toxicity [EC_{50}-72h equal 4.18% and 5.46%].

- Immobilization test with crustacean *Daphnia magna*

Crustancean *D. magna* appeared much more sensitive than algae to contaminants present in the samples. EC_{50}-72h values for the majority of the samples fall within the range from 0.05% (sample of 20% HCl with additions from acid tank, used in the first stage of fracturing) to 8.76% (sample of flowback fluid sampled after drilling out the plug 2). The fluid sampled after drilling out the plug 5/6 appeared to be the least toxic - EC_{50}-72h equal 65.81% (see Table 3).

Table 3. Results of ecotoxicity studies on fluid samples from hydraulic fracturing treatments, obtained in immobilization test with crustacean *Daphnia magna*

Sample No.	Type of sample	EC_{50}-24h [% v/v] [95% confidence interval]	EC_{50}-48h [% v/v] [95% confidence interval]
1	20% HCl with additions from acid tank, used in the first stage of fracturing	0,05 (0,01-0,09)	0,05 (0,01-0,09)
3+W 1:1	Fracturing fluid with addition of resin-coated silica sand, diluted with water sample (W) from open-air reservoir in proportion 1:1	11,22 (7,35-15,92)	5,56 (3,37-8,57)
4	Flowback fluid sampled after drilling out the plug 2	8,76 (5,37-12,81)	8,76 (5,37-12,81)
7	Flowback fluid sampled after drilling out the plug 5/6	89,19 (77,7-98,3)	65,81 (57,4-74,8)
12a	Flowback fluid sampled after nitrogen treatment	0,70 (0,51-0,89)	0,64 (0,49-0,81)
15	Flowback fluid sampled after nitrogen treatment and before closing the well	2,30 (1,89-2,71)	1,57 (1,27-1,94)

It should be stressed that in the case of the majority of samples an increase of test reaction rate was taking place in 24 to 48 hours. The increase was reflected by drop in EC_{50} values.

- Survival test on fish Lebistes reticulatis

Technological fluids (samples of 20% HCl with additions from acid tank and both flowback fluids sampled after nitrogen treatment) appeared toxic to fish at concentrations of LC_{50}-96h equal 0.07%, 9.97% and 9.19%, respectively. The remaining samples were found to be much less toxic (Table 4).

Table 4. Results of ecotoxicity studies on fluid samples from hydraulic fracturing treatements, obtained in survival test on fish *Lebistes reticulatis*

Sample No.	Type of sample	EC_{50}-24h [% v/v] [95% confidence interval]	EC_{50}-48h [% v/v] [95% confidence interval]	EC_{50}-96 [% v/v] [95% confidence interval]
1	20% HCl with additions from acid tank, used in the first stage of fracturing	0,07 (0,05-0,13)	0,07 (0,05-0,13)	0,07 (0,05-0,13)
3+W 1:1	Fracturing fluid with addition of resin-coated silica sand, diluted with water sample (W) from open-air reservoir in proportion 1:1	50 (39,9-59,9)	42,59 (34,45-53,4)	42,59 (34,45-53,4)
4	Flowback fluid sampled after drilling out the plug 2	60,20 (51,8-68,9)	60,20 (51,8-68,9)	60,20 (51,8-68,9)
7	Flowback fluid sampled after drilling out the plug 5/6	>100	>100	>100
12a	Flowback fluid sampled after nitrogen treatment	15,59 (11,38-19,59)	12,50 (8,82-15,98)	9,97 (6,64-13,3)
15	Flowback fluid sampled after nitrogen treatment and before closing the well	17,89 (15,99-19,78)	11,15 (9,85-13,45)	9,19 (7,98-10,49)

In the case of three samples (fracturing fluid with addition of silica sand and both flowback fluid sampled after nitrogen treatment), a time increase of test reaction rate was found.

- Test of seed germination and early growth of plants – Phytotoxkit ™

The studied samples appeared more harmful in causing inhibition of growth of roots than in inhibition of seed germination. The sample of 20% HCl with additions from acid tank was the most toxic as EC_{50}-72h (inhibition of growth of roots) was equal 1.44% for *Sorghum,* 1.20% for *Lepidium* and 1.81% for *Sinapsis* (see Table 5). Two samples of flowback fluid taken after nitrogen treatment were much less harmful, with EC_{50}-72h values (inhibition of growth of roots) ranging from 5.33% to 15.42%. The remaining samples were not characterized by high toxicity.

4.2 Toxicity profiles of individual samples

Toxicity profiles were established for the studied samples by arranging end points of test reactions from the highest to lowest $LC(EC)_{50}$-t. Simultaneously acute toxic units Tu_a were calculated and toxicity in relation to individual test organisms was established.

Sample no. 1 (20% HCl with additions from acid tank, used in the first stage of fracturing) displayed high toxicity on higher plants and extreme toxicity on all the other bioindicators. Its TU_a values were ranging from 25 to 2 000 (Table 6).

Sample no. 3+W (fracturing fluid with addition of resin-coated silica sand and diluted with water) displayed low toxicity to toxicity on higher plants, fish and algae and high toxicity on crustaceans (Table 7).

Sample no. 4 - (W) (flowback fluid sampled after drilling out the plug 2) displayed toxicity on all the test organisms, except for crustaceans, for which it appeared highly toxic (Table 8). Its TU_a values were ranging from 1.66 to 11.42.

Sample no. 7 (flowback fluid sampled after drilling out the plug 5/6) appeared to be non-toxic or of low toxicity on higher plants and fish and of toxicity of the class II on algae and crustaceans (Table 8). Its TU_a values were ranging from 0 to 1.52.

Table 5. Results of ecotoxicity studies on fluid samples from hydraulic fracturing treatments, obtained in tests of seed germination and early growth of plants – Phytotoxkit ™

Sample No.	Type of sample	***Sorghum saccharatum*** **EC_{50}-72h[% v/v] [95% confidence interval]**		***Lepidium sativum*** **EC_{50}-72h[% v/v] [95% confidence interval]**		***Sinapsis alba*** **EC_{50}-72h[% v/v] [95% confidence interval]**	
		seed germination inhibition	root growth inhibition	seed germination inhibition	root growth inhibition	seed germination inhibition	root growth inhibition
1	20% HCl with additions from acid tank, used in the first stage of fracturing	1,88 (1,33-2,45)	1,44 (1,12-1,76)	3,99 (3,10-4,85)	1,20 (0,98-1,44)	3,84(2,98-4,85)	1,81 (1,21-2,41)
3+W 1:1	Fracturing fluid with addition of resin-coated silica sand, diluted with water sample (W) from open-air reservoir in proportion 1:1	45,19 (41,63-48,92)	64,04 (60,32-67,84)	>100*	61,05 (57,15-64,95)	87,79 (78,42-94,89)	>100**
4	Flowback fluid sampled after drilling out the plug 2	35,23 (31,11-39,33)	34,88 (30,58-38,42)	47,32 (43,12-51,44)	39,99 (35,59-45,01)	38,32 (34,12-42,58)	25,11 (23,20-28,12)
7	Flowback fluid sampled after drilling out the plug 5/6	>100	>100**	>100	>100	>100***	>100***
12a	Flowback fluid sampled after nitrogen treatment	28,84 (18,9-25,73)	5,33 (4,10-6,53)	8,84 (7,34-9,44)	7,64 (6,14-8,25)	12,50 (10,20-14,80)	11,51 (9,90-13,11)
15	Flowback fluid sampled after nitrogen treatment and before closing the well	24,06 (21,90-26,16)	7,03 (5,53-8,63)	14,01 (11,8-16,21)	12,61 (10,21-14,99)	15,42 (13,12-17,72)	13,25 (11,358-15,15)

* Seed germination inhibition in 100% concentration was equal 33%

** Root growth inhibition in 100% concentration was equal 48.6%

*** Inhibition of seed germination and root growth in 100% concentration was equal 30%

Table 6. Toxicity profile for Sample no. 1 - 20% HCl with additions from acid tank, used in the first stage of fracturing

Test organism	Toxicity evaluation criteria	Endpoint of test reaction $LC(EC)_{50}$-t [% v/v]	TU_a	Toxicity class	Determination of toxicity
Lepidium sativum	Seed germination	3,99	25,06	III	High toxicity
Sinapis alba	Seed germination	3,84	26,04	III	High toxicity
Sorghum saccharatum	Seed germination	1,88	53,19	III	High toxicity
Sinapis alba	Growth of roots	1,81	55,25	III	High toxicity
Sorghum saccharatum	Growth of roots	1,44	64,44	III	High toxicity
Lepidium sativum	Growth of roots	1,20	83,33	III	High toxicity
Lebistes reticulates	Survivability	0,07	1420	IV	Extreme toxicity
Daphnia magna	Immobilisation	0,05	2000	IV	Extreme toxicity
Raphidocelis subcapitata	Growth	0,05	2000	IV	Extreme toxicity

Table 7. Toxicity profile for Sample no. 1+W 1:1 - Fracturing fluid with addition of resin-coated silica sand, diluted with water sample (W) from open-air reservoir in proportion 1:1

Test organism	Toxicity evaluation criteria	Endpoint of test reaction $LC(EC)_{50}$-t [% v/v]	TU_a	Toxicity class	Determination of toxicity
Lepidium sativum	Seed germination	>100	<1	I	Low toxicity
Sinapis alba	Growth of roots	>100	<12	I	Low toxicity
Sinapis alba	Seed germination	87,79	1,14	II	Toxic
Sorghum saccharatum	Growth of roots	64,04	1,56	II	Toxic
Lepidium sativum	Growth of roots	61,05	1,62	II	Toxic
Sorghum saccharatum	Seed germination	45,19	2,12	II	Toxic
Lebistes reticulates	Survivability	42,59	2,34	II	Toxic
Raphidocelis subcapitata	Growth	36,06	2,73	II	Toxic
Daphnia magna	Immobilisation	5,56	17,99	III	High toxicity

Table. 8. Toxicity profile for Sample no. 4 - Flowback fluid sampled after drilling out the plug 2

Test organism	Toxicity evaluation criteria	Endpoint of test reaction $LC(EC)_{50}$-t [% v/v]	TU_a	Toxicity class	Determination of toxicity
Lebistes reticulates	Survivability	60,20	1,66	II	Toxic
Lepidium sativum	Seed germination	47,32	2,11	II	Toxic
Lepidium sativum	Growth of roots	39,99	2,50	II	Toxic
Sinapis alba	Seed germination	38,32	2,61	II	Toxic
Sorghum saccharatum	Seed germination	35,32	2,84	II	Toxic
Sorghum saccharatum	Growth of roots	34,88	2,87	II	Toxic
Sinapis alba	Growth of roots	35,11	3,98	II	Toxic
Raphidocelis subcapitata	Growth	13,56	7,37	II	Toxic
Daphnia magna	Immobilisation	8,76	11,42	III	High toxicity

Table 9. Toxicity profile for Sample no. 7 - Flowback fluid sampled after drilling out the plug 5/6

Test organism	Toxicity evaluation criteria	Endpoint of test reaction $LC(EC)_{50}$-t [% v/v]	TU_a	Toxicity class	Determination of toxicity
Lebistes reticulates	Survivability	>100	0	0	Non
Lepidium sativum	Seed germination	>100	0	0	Non
Lepidium sativum	Growth of roots	>100	0	0	Non
Sorghum saccharatum	Seed germination	>100	0	0	Non
Sinapis alba	Seed germination	>100	<1	I	Low toxicity
Sinapis alba	Growth of roots	>100	<1	I	Low toxicity
Sorghum saccharatum	Growth of roots	>100	<1	I	Low toxicity
Raphidocelis subcapitata	Growth	87,12	1,15	II	Toxicity
Daphnia magna	Immobilisation	65,81	1,52	II	Toxicity

Sample No. 12 a (Flowback fluid sampled after nitrogen treatment) displayed toxicity or high toxicity on almost all of the the test organisms, except for crustaceans, and extreme toxicity on crustaceans (Table 10). Table 8). Its TU_a values were changing in a wide range, from 4.38 to 156.25.

Table. 10. Toxicity profile for Sample no. 12a - Flowback fluid sampled after nitrogen treatment

Test organism	**Toxicity evaluation criteria**	**Endpoint of test reaction $LC(EC)_{50}$-t [% v/v]**	**TU_a**	**Toxicity class**	**Determination of toxicity**
Sorghum saccharatum	Seed germination	22,84	4,38	II	Toxic
Sinapis alba	Seed germination	12,50	8,00	II	Toxic
Sinapis alba	Growth of roots	11,51	8,61	II	Toxic
Lebistes reticulates	Survivability	9,97	10,03	III	High toxicity
Lepidium sativum	Seed germination	8,84	11,31	III	High toxicity
Lepidium sativum	Growth of roots	7,64	13,09	III	High toxicity
Sorghum saccharatum	Growth of roots	5,33	18,76	III	High toxicity
Raphidocelis subcapitata	Growth	4,18	23,09	III	High toxicity
Daphnia magna	Immobilisation	0,64	156,25	IV	Extreme toxicity

Sample No. 15 (Flowback fluid sampled after nitrogen treatment) displayed toxicity generally on all the higher plants and high toxicity on the remaining bioindicators (Table 11). Its TU_a values were changing in a range from 4.16 to 63.69.

Table 11. Toxicity profile for Sample no. 15 - Flowback fluid sampled after nitrogen treatment and before closing the well

Test organism	Toxicity evaluation criteria	Endpoint of test reaction $LC(EC)_{50}$-t [% v/v]	TU_a	Toxicity class	Determination of toxicity
Sorghum saccharatum	Seed germination	24,06	4,16	II	Toxic
Sinapis alba	Seed germination	15,42	6,49	II	Toxic
Lepidium sativum	Seed germination	14,01	7,14	II	Toxic
Sinapis alba	Growth of roots	13,25	7,55	II	Toxic
Lepidium sativum	Growth of roots	12,61	7,93	II	Toxic
Lebistes reticulates	Survivability	9,19	10,88	III	High toxicity
Sorghum saccharatum	Growth of roots	7,03	14,22	III	High toxicity
Raphidocelis subcapitata	Growth	5,46	18,32	III	High toxicity
Daphnia magna	Immobilisation	1,57	63,69	III	High toxicity

4.3. Determination of safe concentrations of the studied samples for aqueous organisms

Safe concentration values were calculated for hydraulic fracturing fluids which match the requirement CMC ≤ 0.3 TU_a, that is survival of aqueous organisms for 1 hour from the time when contaminants get into the water. Taking into account 99% confidence level and 99% probability it may be stated that the lowest values of safe concentrations were obtained for 20% HCl with additions from acid tank, used in the first stage of fracturing(0.0017%), flowback fluid sampled after nitrogen treatment (0.017%) and flowback fluid sampled after nitrogen treatment and before closing the well (0.066%) (see Table 12).

Table 12. Values of safe concentrations of samples of hydraulic fracturing fluids for aqueous organisms matching the requirement CMC ≤ 0.3 TU_a

Sampl e No.	Type of sample	$TU_{a\ max}$	RPMF		Safe concentration (SC) [% v/v]	
			95-95*	99-99**	95-95*	99-99**
1	20% HCl with additions from acid tank, used in the first stage of fracturing	2000	3,1	8,7	**0,0048**	**0,0017**
3+W 1:1	Fracturing fluid with addition of resin-coated silica sand, diluted with water sample (W) from open-air reservoir in proportion 1:1	17,99	3,4	10,4	**0,490**	**0,160**
4	Flowback fluid sampled after drilling out the plug 2	11,42	2,1	4,3	**1,251**	**0,611**
7	Flowback fluid sampled after drilling out the plug 5/6	1,52	2,4	5,7	**8,224**	**3,462**
12a	Flowback fluid sampled after nitrogen treatment	156,25	3,5	11,3	**0,055**	**0,017**
15	Flowback fluid sampled after nitrogen treatment and before closing the well	63,69	2,8	7,1	**0,168**	**0,066**

* 95% confidence level and 95% probability
** 99% confidence level and 99% probability

Successively, Sample no. 3+W (1:1) (fracturing fluid with addition of resin-coated silica sand) should be diluted to 0.16%, and that of flowback fluid taken after drilling out the plug 2 – to 0.61%. The highest safe concentration (3.462%) was recorded in the case of the sample of flowback fluid taken after drilling out the plug 5/6. Safe concentrations determined at 95% confidence level and 99% probability are two to three times higher.

5. Conclusions

5.1. The studied fluids appeared harmful to aqueous organisms and highly toxic especially to invertebrates - crustaceans *Daphnia magna* and algae. They appeared less harmful to higher plants – sorghum, peppergrass, and charlock.

5.2. The highest values of acute toxic units TU_a were obtained for the samples of 20% HCl with additions from acid tank, used in the first stage of fracturing (2 000), flowback fluid taken after nitrogen treatment (156.25) and that of flowback fluid taken after nitrogen treatment and before closing the well (63.69). The values are close to those obtained for liquid waste generated from oil refineries and pharmaceutical plants in Poland. The sample of flowback fluid taken after drilling out the plug 5/6 was the least harmful (TU_a = 1.52).

5.3. The studied fluids represent pollution risks for water and soil environment. Their safe concentrations at 99% confidence level and 99% probability range from 0.0017% (Sample no. 1) to 3.462% (Sample no. 7).

5.4. The flowback fluids should be subjected to treatments such as those provided for harmful liquid industrial waste.

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