The environment and shale gas exploration

RESULTS OF STUDIES ON THE SOIL-WATER ENVIRONMENT, AMBIENT AIR ACOUSTIC CLIMATE, PROCESS FLUIDS AND WASTES

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THE ENVIRONMENT AND SHALE GAS EXPLORATION

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GLOSSARY

seismic surveying – a non-invasive method for investigation of deep geology that enables investigation of a particular area for the occurrence of crude oil, natural gas or other mineable resources. Acoustic waves generated by the so-called vibrator trucks travel deep into the Earth and the image created by reflected waves that return to the ground surface is recorded by receivers called geophones. The acquired data enable the identification of optimal drilling locations.

EC – effective concentration – the concentration of a substance (or of a mixture) that induces observable changes in test organisms, e.g. immobilization, inhibition of biochemical processes or growth. Test result is expressed as concentration that inhibits a given physiological process by 50% after a specific time of exposure – EC50.

good water status – the status of uniform bodies of water which is defined as good or better in terms of quantity and chemistry (according to the Water Law of 18 July 2001, as amended).

Main Commercial Aquifer (MCA) – top commercial aquifer which serves as the main source of water supply, having a dominant range and resources within a hydrogeologic unit of the Hydrogeological Map of Poland (scale: 1:50 000) and meeting the applicable criteria in terms of thickness (> 5m), potential productivity of water wells (>5 m^3/h) and quality requirements for potable water untreated or pretreated using simple technical processes.

Principal Aquifer (PA) – a reservoir of special regional importance to the existing and prospective public water supply that meets specified quantitative and qualitative criteria: potential water well productivity >70 m^3/h, water intake capacity >10 000 m^3/h, transmissivity >10 m^2/h; water untreated or pretreated using available simple and economically viable technologies is ready for consumption.

IC – inhibitory concentration (inhibiting the growth, chlorophyll generation, etc.) – the concentration of a substance (or of a mixture) that in sub-lethal tests (where the organisms are not killed) inhibits physical and biological activity of test organism by a specific percent) (e.g. IC25).

well integrity – absolute tightness of the borehole where the accessed interval is effectively isolated in the borehole from the overlying intervals so that any upward flow or migration of reservoir fluids (e.g. gas) as result of pressure gradient or diffusion flow through the cement sheath is prevented.

uniform part of groundwater bodies – a specified groundwater volume in an aquifer or a system of aquifers (according to the Water Law of 18 July 2001, as amended).

$\mathbf{L_{Aeq\,D}}$ – equivalent daytime noise level adjusted against the A frequency profile; refers to 8 consecutive least advantageous daytime hours. (6:00 AM through 10:00 PM)
$\mathbf{L_{Aeq\,N}}$ – equivalent night-time noise level adjusted against the A frequency profile; refers to 1 least advantageous night-time hour (10:00 PM through 6:00 AM)

LC – lethal concentration – the concentration of a substance (or of a mixture) that is lethal to a specified number (expressed as %) of population members after a specified time of exposure, e.g. LC50, LC100

LOEC – lowest observed effect concentration – the lowest concentration of a substance (or of a mixture) which (in a specified time of exposure) has an effect causing changes in test organisms.

unconventional hydrocarbon accumulation – an accumulation of hydrocarbons (gas, oil/gas, gas condensate) which lacks a well defined down-dip petroleum/water contact, characterized by

low permeabilities (less than 0.1 mD – normally in the order of μD (micro-Darcy)) of tight sandstone and carbonate rocks or mudstone shale rocks of ultra-low permeabilities, in the order of nano-Darcy. Moreover, unconventional accumulations include coalbed methane gas and submarine hydrate deposits in permafrost areas. According to some sources, unconventional hydrocarbons include deep water gas deposits and synthesis gas (syngas) from in situ coal gasification. What makes unconventional resources apart is the necessity to apply energy to the accumulation in order to induce gas or oil flow to the borehole. Tight and shale gas/oil is produced using directional (sometimes vertical) wells with an over 1000 m long horizontal leg that is sequentially fracture stimulated in 100 m long intervals.

NOEC – no observed effect concentration – the highest concentration of a substance (or of a mixture) which (in a specified time of exposure) has no effects causing changes in test organisma.

groundwater budget area – a hydrological unit established to assess renewable and available groundwater resources, including the degree of their development.

PA buffer area – a part (or parts) of aquifer recharge area where land use prohibitions, injunctions or limitations are imposed in order to protect groundwater quality and resources.

groundwater resistance to pollution – geology and hydrogeology-based aquifer characteristics that control aquifer's sensitivity to existing or potential pollution by delaying or limiting migration of pollutants.

well – a completed science, exploratory, appraisal or production borehole where drilling operations have been completed and X-mas tree installed to produce hydrocarbons. The term drilling wells is used throughout this document.

top aquifer (TA) – topmost aquifer or a system of hydraulically interconnected aquifers.

flowback fluid (water) – liquid fraction that is recovered on the ground surface on removal of plugs and wellhead valve opening after hydraulic fracture stimulation. Initially, the flow is induced by overpressure established in the borehole by the injected fracturing fluid. Subsequently, flowback is stimulated by gas lift or pumping. If reservoir conditions are favourable, some flowback fluid is brought to the surface by gas reservoir pressure. It is accepted arbitrarily that flowback fluid is recovered from the well up to the installation of X-mas tree. The fluid recovered from the well at the stage of production is called production water.

fracturing (fracking) fluid – the fluid used in hydraulic fracture stimulation processes. Typically, it is composed of water and sand that is deposited in the induced fractures (approx. 99.5%) and of chemical additives (approx. 0.5%) that help to minimize friction during the flow of fracturing fluid through the borehole, to maintain a neutral pH, inhibit corrosion and scale deposition. Chemical additives that improve hydraulic fracturing processes are commonly used in beauty products, cleaning and disinfecting agents, food additives and household products.

test site – here: a section of the space around a drilling well, in particular the drill site and its immediate neighbourhood. Test site boundaries are not marked, they are delimited by theoretical range of potential environmental impacts from the drill site and may vary from one analysed environmental component to another.

proppant – natural sand or ceramic granules added to the fluid (accounting for approx. 4.5% of the fluid) that is used for hydraulic fracture stimulation. Proppant prevents the induced fractures from collapsing and enables the flow of gas through reservoir rocks.

groundwater risk assessment – a relative assessment of the potentiality for penetration of pollutants to the aquifers, considering geology and hydrogeological conditions on the path of migration from the source of pollution to a water abstraction point.

well stimulation – a procedure that involves fracturing or acid treatment of the reservoir interval so as to enhance flow of reservoir fluid to the borehole. Well stimulation is a precondition for enabling the flow in unconventional accumulations.

hydraulic fracturing – the process of rock formation fracturing with dedicated fracturing fluids composed of water and sand mixture (approx. 99.5%) and chemical additives (approx. 0.5%). A well stimulation method that is also used in shale gas production.

flow testing (gas flow testing) – short- and long-term testing – in a short-term test, gas is produced from the well over a period of two or three weeks that follow the fracture stimulation. Gas flow is initiated by pressure release in the borehole and building up a pressure gradient. Dual-phase flowback fluid is produced during a short-term test and, if successful, the test is followed by gas production. Normally, the test is conducted until 20% of the injected fracturing fluid is recovered and the flowback production rate falls by 75%. The test reveals the initial effects of fracture stimulation. A long-term test may last a few months or even two years and is intended to establish initial gas production rate in the first month, as well as to estimate the productivity drop rate in order to assess recoverable gas reserves per well.

chronic toxicity – adverse effects on test organisms from exposure to a chemical compound (or to a mixture with relatively low concentrations) over a long period of time – normally, 1/10 of a life cycle until the first offspring generation is produced. Sublethal concentrations are used in model tests. Changes in physiological activity, e.g. alimentary, reproductive functions, genetic disorders and organ disturbances are observed and assessed.

acute toxicity – adverse effects on test organisms from exposure to a chemical compound (or to a mixture with relatively high concentrations) that may lead to disturbances of physiological activity and death after a short time of exposure.

commercial aquifer – one or several hydraulically interconnected aquifers with parameters that are suitable for commercial production of potable and process water.

drill site – a site (yard) with an assembled operational drilling rig, support technical facilities and necessary services.

mining plant – according to Geological and Mining Law, a technically and organizationally separate set of assets that are directly intended for Law-regulated extraction of mineables from deposits, in underground coal mines inclusive of coal dressing facilities that are connected with coal extraction process treatment, for underground tankless storage of substances or underground storage of wastes, including mine workings, erected structures, plant and machinery and installations (2011 Journal of Laws No. 163, Item 981, as amended).

plant performing geological works – a technically and organizationally separate set of assets that are directly intended for delivery of geological works, in this specific case for science well drilling under exploration and appraisal projects. Pursuant to Art. 86 of Geological and Mining Law, the provisions on mining plant, its operations and mining rescue shall accordingly apply to exploration and appraisal operations as geological works. *The abbreviation plant or drill site is frequently used in this document.*

groundwater resources available for development – same as **available resources** – in areas with hydrogeologically proven resources or **prospective resources** – in areas where available resources are still to be proved.

available groundwater resources – groundwater resources available for development that are defined as multi-year average of the total groundwater recharge in a specific budget area or unit less multi-year average of the total water debit, which is not expected to result in a serious deterioration of the surface waters that are connected with underground waters and occurrence of a significant damage to groundwater-based terrestrial ecosystems. Available resources are determined so as to not deteriorate groundwater chemistry, considering spatial conditions of occurrence, hydrogeological parameters and hydraulic contacts between aquifers in the water budget area or unit, along with spatial distribution of environmental and hydrogeological limitations to resource development and the existing spatial patterns of groundwater usage. Available resources are determined without indicating specific water abstraction locations or technical/economic conditions.

Summary

This Report has been made in fulfilment of the Contract No. 117/GDOŚ/DON/2012 of 18 July 2012 with subsequent annexes 1–5 thereto, made between: the State Treasury – the Minister of the Environment, represented by Mr. Michał Kiełsznia – General Director of Environmental Protection and the Consortium composed of: Polish Geological Institute – National Research Institute [PGI-NRI] (consortium leader), AGH University of Science and Technology in Kraków [AGH], Gdańsk University of Technology [PG], financed by the National Fund for Environmental Protection and Water Management.

The aim of the project was to determine the environmental impact of the prospection and exploration of unconventional hydrocarbons, including a detailed analysis of the potential and actual impacts on specific environmental compartments, including in particular: the atmosphere, ground surface, soil, surface water and the groundwater. Initially, 5 test sites (TS) around the following exploratory wells were chosen: Lubocino-2H (Lubocino TS), Stare Miasto-1K (Stare Miasto TS), Wysin1 (Wysin TS), Syczyn OU-2K (Syczyn TS) and Zwierzyniec-1 (Zawada TS). During the project, the survey has been expanded to include the test site around Gapowo B-1A exploratory well (Gapowo TS), as well as the studies included in the long-term monitoring of the following test sites: Stare Miasto, Syczyn and Zawada, and around Łebień LE-2H exploratory well (Łebień TS). In total, a diverse range of work was carried out under the project in the area of 7 test sites, located in the Pomeranian Province (5) and Lubelskie Province (2).

Due to the duration of the project and the Operators' work schedules, the research did not always cover full exploration cycles. In two cases (Wysin and Zawada test sites), it was possible to carry out the assessment of the status of the environment prior to drill site development. In these cases the baseline status of the environment was determined with regard to exploratory drilling for unconventional hydrocarbons[1]. In other locations, at the start of the project not only the drill sites were already built, but drilling operations had been conducted as well, and sometimes hydraulic fracture stimulation jobs have been performed beforehand. For those locations the so called as-found status of the environment was determined, and some reference measurements, e.g. for noise or ambient air pollution were performed on completion of drill site operations. The studies on the status of the environment on completion of works were generally performed when the operator reported the completion of rigging down operations and demobilization of fracture stimulation equipment, but not the abandonment of the drill site. Only in one case it was possible to carry out the study of the status of the environment after the notification of well abandonment by the Operator and drill site reclamation (Stare Miasto TS).

The full cycle of research was meant to include:

1. identification of the local conditions and field studies planning,
2. examination of the baseline status of the environment prior to the commencement of exploration,
3. studies while drilling vertical/directional wells,
4. studies during hydraulic fracture stimulation and gas flow testing,
5. examination of the status of the environment on completion of drill site operations,
6. in some cases, monitoring of the status of the environment at a certain time after the completion of downhole operations.

The scope and schedule of research operations were closely dependent not only on frequently changing exploration schedules at each location, but also on an efficient communication between Operators and the research team. It should be emphasized that under the project the Operators cooperated on a voluntary basis and according to the rules adopted under separate contracts / agreements.

Due to frequent changes in Operators' plans and work schedules and an extensive scope of the study, the project has encountered some challenges, nevertheless it was possible to fully achieve the agreed objectives, including:

[1] The study programme did not include works related to the acquisition of seismic data.

1. Environmental baseline study of 2 test sites with regard to:
   - groundwater and surface water status,
   - soil quality in terms of hydrocarbon content and parameters that are relevant to agricultural production,
   - soil gas tests for hydrocarbon and radon concentrations,
   - background noise level,
   - background concentrations of gaseous pollution and particulate matter in ambient air;
2. The original topography of one site was documented using 3D laser scanning;
3. Existing environmental status studies in 4 test sites, as per point 1 above;
4. Measuring with 3D laser scanning loose ground displacement at a slope located above the fracture stimulated horizontal wellbore section;
5. Drilling waste (cuttings and spent mud) from target shale formations in six exploratory wells (plus intervals with potentially higher contents of radioactive elements in two wells) sampled and tested for chemistry and toxicology;
6. Fracturing and flowback fluids sampled following hydraulic fracture stimulation in five exploratory wells and tested for toxicity and chemistry;
7. Natural gas from reservoir formations of 5 exploratory wells sampled and tested for chemistry and isotopic composition;
8. Continuous measurements of the noise level at drill site boundary and the nearest buildings during drilling operations at 6 test sites;
9. Continuous measurements of the noise level at drill site boundary and the nearest buildings during hydraulic fracture stimulation jobs at 5 test sites;
10. Air pollution monitored while drilling six exploratory wells and during hydraulic fracture stimulation of five exploratory wells;
11. Additional soil and groundwater quality tests following a drill site incident;
12. Additional soil gas and groundwater tests performed at one site to supplement available data and enable a reliable interpretation of results;
13. Environmental status determination as per point 1, immediately following the completion of exploratory operations at 5 test sites;
14. Environmental status determination on drill site abandonment and reclamation at 1 test site, including:
    - ground and surface water status,
    - soil quality in terms of hydrocarbon content and parameters that are relevant to agricultural production;
15. Environmental status assessment at 1 test site after 2.5 years from multistage hydraulic fracture stimulation of the well and on drill site abandonment (groundwater status and soil quality tests);
16. Environmental status assessments in the vicinity of 2 test sites, made after one year of hydraulic fracture stimulation and gas-flow tests (groundwater status, soil gas composition and measurements of soil emissions to the atmosphere);
17. The results of seismological monitoring, as delivered by the Central Mining Institute at 2 test sites, were attached to the conclusions.

The results of all the studies together with the characteristics of individual test sites, a description of testing methodology, interpretation and programs for continued monitoring were delivered to the Contracting Authority in accordance with the project schedule. In total, 4 interim reports on work carried out in four sub-stages of the project were prepared along with 7 final reports on the studies carried out at 7 test sites (Lubocino, Stare Miasto, Syczyn, Zawada, Wysin, Łebień, Gapowo), 3 supplements to the final reports (for the Stare Miasto, Syczyn and Zawada test sites) and this summary report, which includes the summary of all the work carried out, a comparison of particular test sites and results obtained therein, as well as an overall assessment of the environmental impact from drilling and hydraulic fracture stimulation-based exploration, along with recommendations for the monitoring of similar operations, potential changes in the environmental status therefrom, and diverse conclusions or recommendations that have arisen from the experience gained throughout the delivery of this project.

The main conclusions regarding the extent of the environmental impact from drilling operations and hydraulic fracture stimulation for unconventional hydrocarbons can be summarized as follows:

1. In Poland, potentially gas-bearing formations occur at great depths and are overlain by deposits that provide excellent sealing capability with regard to potential upward migration of fluids or gas to the main commercial aquifers and the ground surface, due to low porosities and permeabilities of the caprock and the absence of conductive fault zones.
2. Hydraulic fracture stimulation of individual wells does not induce seismic vibrations that are noticeable on the ground surface. Moreover, recorded vibrations do not exceed the permitted vibration limit values for the stability of erected structures under Polish Standard PN-85/B-02170.
3. The noise level in immediate drill site vicinity in a short term exceeds the permitted daytime values for built-up areas. The intermittent short-term exceedances are only connected with the operation of generator sets and high-output pumps at some stages of hydraulic fracture stimulation jobs. So far, these well stimulation techniques have been performed in Poland only in daytime hours.
4. The operation of some high-power combustion devices can cause a temporary increase in the concentration of gases (fuel combustion products) in the air. A temporary increase in the concentrations of C_2–C_{12} hydrocarbons and volatile organic compounds in the air was also observed.
5. Anomalous concentrations of methane gas and its heavier homologues, gaseous C_2–C_4 alkenes, as well as of the carbon dioxide and the presence of hydrogen in the soil gas have been observed in some regions of Poland. The reason for this is mainly microbial fermentation of simple organic compounds (which is confirmed by isotopic composition studies), while the drill site sheet lining prevents aeration of soil and may cause an increase in the concentrations.
6. In addition to the effects of recent microbial processes, in the Lublin region natural elevated micro concentrations of total C_2–C_5 alkanes were found in the soil gas, an evidence of migration from deposits, probably from Upper Carboniferous coal beds. The presence of these gases in the near-surface zone may be the result of a drilling-induced disturbance to the continuity of strata containing a natural accumulation of hydrocarbons in the Carboniferous deposits. In light of isotope studies it should be concluded that certainly this is not a thermogenic gas associated with Silurian accumulations.
7. Elevated radon concentrations in drilling areas, which could indicate the presence of radionuclides in the gas and its migration along the borehole to the ground surface, were not observed.
8. Extractive waste tests for radioactivity showed a slightly increased concentration of radionuclides ^{226}Ra and ^{40}K. The activity of ^{40}K in drilling waste was slightly above average, but it was on the level naturally occurring in the environment, and it probably results from the use of potassium in drilling mud preparation process or from drilling mud contact with rocks which have slightly higher than average ^{40}K concentrations. Also, ^{226}Ra concentration is probably the result of contact with rocks having a slightly higher than average ^{226}Ra concentration.
9. Ecotoxicological studies have indicated that the drilling mud and drilling wastes may pose a risk (in the case of improper management) to the biota in the event of an uncontrolled release to the environment; therefore, regulatory provisions and procedures relating to the transport, recovery / disposal processes should be strictly followed.
10. Water abstraction under relevant water permits at all test sites had no effect on the status of groundwater resources and did not cause a lowering of the groundwater level.
11. The study showed no negative impact of exploration on the ground and surface water chemistry in the observed period of time. There was no contamination of the groundwater as a result of well stimulation, but the obtained results indicate that operations made improperly on the drill site may potentially result in penetration of certain substances from the surface to the top aquifer. However, the reported cases were limited to small areas only.
12. Drill site operations had no adverse effects on soil quality for farming, probably because the top soil has been protected by storing in embankments around the site. However, a prolonged load may have an effect on the degree of subsoil compaction, adversely affecting agricultural production until the initial conditions are restored.

13. Drill site operations have had a relatively short-term effect on the landscape and should not leave any significant imprint on the landscape upon completion of operations.
14. Drill sites may have a potential direct, but short-term, adverse impact on the environment, including high value natural areas and the species subject to individual protection, via the following environmental compartments: air (related to the predominant wind direction), water (related to the direction of surface runoff) and an increased noise level. No indirect impact was detected, involving, e.g. hydrographic conditions, permanent air pollution with gases or particulates, etc.

Delivery of further exploratory operations, and in the future production of unconventional hydrocarbons in Poland will require, above all, to establish – as soon as possible – the environmental baseline in potential drilling locations in terms of ground and surface water status, including background concentrations of methane in the groundwater, soil gas methane, the condition of the existing road infrastructure, to plan for transmission infrastructure and to carry out an assessment of the environmental impact from the implementation plans.

Due to the scale of works, in terms of water requirements, the stage of shale gas production will differ significantly from the current prospection and exploration stage in Poland. Considering the above, it is recommended to focus the legislative solutions, recommendations, and the development of technology so as to enable the reuse of water from other industrial processes (e.g. water from underground mining drainage, treated sewage, water from storm drains, water from the biogas plants, etc.) in the fracture stimulation operations.

A separate task is to estimate the amount of drilling waste generated in various regions of production at drilling and fracture stimulation stages, as well as to define the possibilities for proper handling of wastes, considering both their quantity and properties.

Ensuring safety of the environment and of the population in production areas will require an adequate control of operations and the establishment of uniform monitoring – independent from entrepreneurs – of the environment (topmost and commercial aquifers, as well as soil gas in immediate drill site vicinity). Such monitoring must be strictly adapted to the local geological and hydrogeological conditions, should be independent and guarantee reliability and comparability of results. Therefore, government services seem to be best prepared for the coordination of activities in this area (i.e. acting as general contractor with the involvement of other entities that meet specific criteria as subcontractors).

District mining offices are responsible for inspection of plants carrying out geological and mining works. The plans to increase their number, employment and funding seem to guarantee a proper delivery of these operations and ensure compliance with the best practices available in terms of technology[2].

To make the process of unconventional oil and gas prospection and exploration entirely safe from the point of view of the environment and population safety, an independent long-term monitoring of the environment should be set up in prospective and developed areas, whereas the Inspectorate of Environmental Protection – preferably acting in consultation with the mining offices[3] – should be formally notified of delivery of works so as to enable it to inspect the most critical stages of operations[4].

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[2] The Ordinance establishing a new District Mining Office in Gdańsk took effect on 1 April 2015. The jurisdiction of the new mining office covers the area of Pomorskie, Kujawsko-Pomorskie Provinces and maritime areas of the Republic of Poland.

[3] On 4 April 2014, an agreement was signed between the State Mining Office and the Chief Inspector of Environmental Protection on the cooperation in the field of monitoring of compliance with environmental regulations at each stage of unconventional oil and gas prospection/exploration/production operations. The cooperation takes place on the following levels: the central level – between the Chief Inspector of Environmental Protection and the President of the State Mining Office, and on the local level – between provincial environmental protection inspectorates and the directors of regional mining offices.

[4] The amended Act on the Freedom of Economic Activity took effect on 1 January 2015. The Act provides for the principles of supervision over economic activities carried out, inter alia, in the field of exploration and production of mineables and exploitation of minerals under mining ownership. The application of Art. 79, Art. 80a, Art. 82 and Art. 83 of the Act of July 2, 2004 on the Freedom of Economic Activity (defining the limits of the inspection of economic activity) was excluded with regard to the entrepreneurs engaged in prospection, exploration and production of major mineables under mining ownership (including hydrocarbons). Following the amendment, the authorities are no longer obliged to notify an entrepreneur beforehand of the intention to carry out an inspection, although they are obliged to conduct inspections at the premises of the entrepreneur and during his working hours. Moreover, the authorities are permitted to carry out several inspections simultaneously and there is no time limit for their delivery. The new regulations apply to the inspections that are carried out by the mining supervisory authorities and the Inspectorate of Environmental Protection.

To avoid local conflicts, entrepreneurs engaged in exploration and, in the future, production of unconventional hydrocarbons should establish and make public the rules for safe vehicular traffic on drill site access roads. Noise monitoring carried out at the exploration stage will allow to collect data on the actual noise level that will be needed if any complaints are raised by the residents, as well as will enable the design of effective methods for informed control of noise generated during drilling and fracture stimulation operations at the pre-production stage.

1 Foreword

This Report has been made in fulfilment of the Contract No. 117/GDOŚ/DON/2012 of 18 July 2012 with subsequent annexes 1–5 thereto, concluded between: the State Treasury – the Minister of the Environment, represented by Mr. Michał Kiełsznia – General Director of Environmental Protection and the Consortium composed of: Polish Geological Institute – National Research Institute [PGI-NRI] (consortium leader), University of Science and Technology in Cracow [AGH], Gdańsk University of Technology [PG], financed from funds of the National Fund for Environmental Protection and Water Management.

The aim of the project was to determine the environmental impact of works related to the exploration and appraisal of unconventional hydrocarbon accumulations, including a detailed analysis of the potential and actual impacts on particular environmental compartments, including especially: the atmosphere, ground surface, soil, surface water and the groundwater. Initially 5 test sites (TS) around the following exploratory wells were chosen: Lubocino-2H (Lubocino TS), Stare Miasto-1K (Stare Miasto TS), Wysin-1 (Wysin TS), Syczyn OU-2K (Syczyn TS) and Zwierzyniec-1 (Zawada TS). During the project, the research has been expanded to include the test site around Gapowo B-1A exploratory well (Gapowo TS), as well as research included in the long-term monitoring in the following test sites: Stare Miasto, Syczyn and Zawada, and around Łebień LE-2H exploratory well (Łebień TS). In total, a diverse range of works was delivered under the project in the area of 7 test sites, located in the Pomeranian Voivodeship (5) and Lubelskie Voivodeship (2).

Due to the duration of the project and work schedules of Operators, research did not always cover full exploration cycles. In two cases (Wysin and Zawada test sites), it was possible to carry out the assessment of the state of the environment prior to drill site development. It was assumed that in these cases the so called base-line status of the environment was determined in relation to the exploration of unconventional hydrocarbon accumulations by drilling (seismic data acquisition delivery was not included in the scope of the project). In other locations, at the start of the project, not only the drill sites were already built, but drilling operations had been conducted as well, and sometimes hydraulic fracture stimulation jobs were performed beforehand. For those locations the so called existing status of the environment was determined, and some reference measurements, e.g. for noise or ambient air pollution were performed on completion of drill site operations. The studies of the status of the environment on completion of works were generally performed when the operator reported the completion of rigging down operations and demobilization of fracture stimulation equipment, but not the abandonment of the drill site. Only in one case it was possible to carry out the study of the status of the environment after the notification by the Operator of well abandonment and drill site reclamation.

Results of surveys and observations may have been successively delivered to the Contracting Authority. This Study has been preceded by the following reports:

- FINAL REPORT on delivery of research activities at Test Site 1 – LUBOCINO,
- FINAL REPORT on delivery of research activities at Test Site 2 – STARE MIASTO,
- FINAL REPORT on delivery of research activities at Test Site 3 – SYCZYN,
- FINAL REPORT on delivery of research activities at Test Site 4 – WYSIN,
- FINAL REPORT on delivery of research activities at Test Site 5 – ZAWADA,
- FINAL REPORT on delivery of research activities at Test Site 6 – ŁEBIEŃ,
- FINAL REPORT on delivery of research activities at Test Site 7 – GAPOWO,
- SUPPLEMENT TO FINAL REPORT on delivery of research activities at Test Site 2 – STARE MIASTO,
- SUPPLEMENT TO FINAL REPORT on delivery of research activities at Test Site 3 – SYCZYN,
- SUPPLEMENT TO FINAL REPORT on delivery of research activities at Test Site 5 – ZAWADA,

which should be regarded as expanded detailed versions of Chapters 3 and 4 of this document.

In addition to a summary of study results and the determination of the environmental impact from shale gas and oil exploration and appraisal operations, the team of authors has formulated under the project several recommendations and guidance for the stakeholders on the development of unconventional hydrocarbon production, including in particular:

– premises behind monitoring of abiotic environment status,

- recommendations for delivery of an efficient control of environmental impact of geological works and production of hydrocarbons,
- recommendations for appropriate location of drill sites (mining plants performing geological works),
- recommendations for good waste and water management.

These conclusions should be considered at delivery of subsequent operations so as to ensure that unconventional hydrocarbons are produced in a manner that is safe to both environment and the population.

2 Survey methodology

2.1 Analysis of available documents

2.1.1 Assessment of geological conditions

The assessment of geological conditions has been made with a view to establish, among other things, the profile of sealing complexes, an analysis of fault zones and of their sealing properties, an analysis of the shale rock sealing formations and for the purposes of water studies.

The assessment was based on available pre-existing data (National Geological Archives) and information provided by the Operators. Paper and/or electronic versions (e.g. .doc, .pdf, .xls formats) and digital data have been analysed as part of desktop work.

Input to the analysis of shale formation sealing included pre-existing data on lithology, stratigraphy and facies from the boreholes, well logging data, seismic cross-sections, as well as a number of geological documentations and projects. Information obtained from PGI-NRI databases (e.g. Central Geological Database) and data available at PGI-NRI's National Geological Archives were used in the assessment. Current geological data, as delivered by the Operators, are discussed in Chapter 2.1.2

The assessment of geological conditions for the purposes of water studies focused on gathering information about mineable deposits located in particular test sites, drafting maps of geological conditions and hydrogeological cross-sections, obtained from geological materials. The following sources were used:

- Detailed geological map of Poland (scale 1:50 000),
- MIDAS Mineral Resource Management and Protection System database,
- Geological documentations and projects (National Geological Archives).

Geological information has been supplemented by current data, as obtained from the Operators. The profiles of drilled water wells or piezometers made by the Operators for the purposes of drill site operation (Lubocino, Stare Miasto, Syczyn, Zawada, Łebień, Gapowo) were used in geological studies and to supplement geological profiles.

It should be noted that the test sites highly varied in terms of knowledge of the local geology, depending on the availability of pre-existing data and the scope of current information, as delivered by the Operators.

2.1.2 Shale formation sealing analysis

The characteristics of sealing complexes, including the location of fault zones and their tightness, have been established on the basis of available pre-existing (PGI-NRI archives) and current seismic and drilling data.

Data that are indispensable for a reliable evaluation of shale formation sealing are:

- well location,
- geophysical well logs (LAS format), full set of interpreted (processed) and raw (unprocessed) data,
- a description of well profile or a graphical lithology profile,
- stratigraphy,
- 2D, 3D seismic data, profiles of average velocities,
- seismic data-based maps of the fracture stimulated horizon,
- structural drilling core description (if available),
- the determination of the existing tectonic compression directions,
- results of micro-seismic monitoring of hydraulic reservoir stimulation (if available),
- records of fracturing fluid/proppant pressures and flow rates,
- sonic scanner, six-arm dipmeter or FMI (Formation Microimager) logs.

The analysis of shale formation sealing at the test sites was contingent on the completeness and quality of data provided by the Concession Operators. Unfortunately, data and information delivered

by the Operators frequently proved insufficient for delivering a full scope of analytical work. Therefore, the adopted methodology differed from one site to another depending on data availability.

Based on pre-existing and current data the following was carried out:

- an analysis of maps and pre-existing lithological, stratigraphic and facies studies of deep wells drilled in the proximity of the analysed drill sites,
- an assessment of geophysical well logs and their interpretation, if possible,
- an analysis of tectonics, based on gravimetry data and pre-existing and/or current seismic profiles,
- fault seal analysis.

An analysis of the rock formation tightness with regard to fracturing fluid filtrate (water solutions) is a pilot project that involves constraints inherent to such undertakings. In order to solve the problem, a methodology for the evaluation of the rock medium's isolation properties must be first worked out in micro-, meso- and macro-scale (petrographic studies and core sample tests for permeability; an analysis of geophysical well logs; reservoir models based on seismic, drilling and other data, respectively). Moreover, a set of data that is required for the deployment of the methodology has to be determined and good practice established, as no previous experience from similar accumulations is available in Poland or it is fragmentary in the case of other countries worldwide. While attempting to compare similar studies from other countries it should be kept in mind that they are based on the local specificity, which – in the worst case – may lead to wrong conclusions on the tightness of the analysed Polish rock formations.

According to the experience from petroleum exploration, the most common sealing rocks are (Downey 1994; in decreasing order of widespread occurrence):

1. fine-grained siliciclastic sediments (shales, clays, silts),
2. evaporites (anhydrites, halite or potassium salts),
3. organic matter-rich rocks,
4. other (clayey sandstones and limestones, cherts, volcanic rocks).

However, the presence of above mentioned lithological types is not a guarantee of good sealing – the permeability of the entire structure depends on the least permeable spots. Moreover, each of these media may be permeable to the filtrate, if pressure gradient of the fracturing fluid is high enough. Furthermore, mechanical strength of the rock medium should be considered due to a high pressure gradient at repeat injections of fracturing fluids at the stage of production.

Potential leaks may occur in more permeable zones, such as: discontinuous and non-homogenous rocks, faults, flexures, fractures, joints, earthquake-induced relaxations in unconsolidated terrigenous sediments, inadequately drilled or abandoned wells, etc.

The analysis of potential fault zones present in the test site area was based on available gravimetric and seismic data.

Seismic modelling is an important element of seismic data interpretation. The models enable, among other things, an adequate geological control of seismic boundaries and wave image analysis.

A synthetic seismogram was built using the SynTool Program by Landmark–Halliburton. The 1D wave field (synthetic seismogram) was based on downhole sonic and density logs. As a general rule, sonic logs did not require a verification by average velocity measurements.

Seismic horizons have been correlated within the analysed seismic profiles so as to assess the continuity of the sealing complexes and identify fault zones.

Gravimetric data were analysed using the same methodology in all test sites. Interpolation grids and data visualization in the form of base and transformed maps were established using: Surfer v.9 software (by Golden Software) and the Potential-field software, as published by USGS (Philips, 1997) and supplemented with additional applications by Stanisław Wybraniec (PGI-NRI). Semi-detailed survey point density allows for development of an interpolation grid with 250x250m cells in which calculation were made using the method of kriging, at a search radius of 2.5 km.

Gravimetric lineaments were determined using the method of Philips et al. (2007), which is based on an analysis of the land curvature and enables to estimate not only the patterns of lineaments, but also the depth to their occurrence. Lineaments are determined in three steps. Horizontal gradient is calculated in the first step. The points located along the maximum gradient axis are recorded in the second step along with additional attributes: axis extension (expressed in degrees) and the depth

to the lineament-source discontinuity. Up to this step the process of calculation is purely automatic (objective). Interpretation input is required in the next third step, whereby the identified points are merged into lineaments. At this stage, it is possible to define a minimal number of the lineament-forming points (e.g. if 5, then four-point sets are not merged, even if they are located at the same line) and the search radius (e.g. if 30°, then adjacent points are merged into a single lineament, provided that the angle between their extensions is less than 30°).

Since the lineament-forming points are established on the basis of information from a given location and in immediately adjacent interpolation grid cells, the degree of lineament detail closely depends on the grid's degree of detail. In other words, a basic map of Bouguer anomalies with grid cells sized 250x250 m allows for calculation of the shallowest and finest lineaments. Since gravity is inversely proportional to the square of the distance from the source of gravity, in gravimetric measurements made on the surface of the Earth the effect of gravity from deep sources is often distorted by usually small, but quite often strong anomalies from shallow sources. In order to ask the question which lineaments continue at higher depths, it is necessary to smooth (filter) the basic map so as to obtain a more or less regional picture. To this end, Fourier domain bandpass filtering was effected. Analytical extensions were made to the following levels: 100 m, 200 m, 400 m, 600 m, 800 m, 1000 m, 1500 m, 2000 m and 5000 m. The basic map was also bandpass filtered in the following filter-transmitted wavelengths: 16–32 km, 8–16 km, 6–12 km, 5–10 km, 4–8 km. Wavelength is understood as the total width of two adjacent anomalies: positive and negative one. Lineaments have been established for each of the output maps and the results of calculation are presented on the maps.

Fault seal analyses have been made in order to check whether there is a risk of vertical migration of the injected fracturing fluid or of hydrocarbons released from the rock along any potential fault zones in the lower Paleozoic formations. Depending on the geological structure and throw magnitude, a faulted zone may form a barrier or a path for migration of fluids presents in the rock mass. A fault seal analysis is made to establish the nature (sealing or transmissivity) of the faults.

A majority of fault seal analyses include the determination of the magnitude of throw, superposition of layers along the fault's plane and fault sealing parameters such as the shale-gouge ratio (SGR). If a wealth of geological and geophysical data is available from a particular area, a 3D geological model can be developed along with a more in-depth analysis. Due to insufficient data, this study is limited to the analysis of the SGR parameter. Therefore, the analysis is incomplete and should be superseded by a more accurate analysis as soon as new data are available.

Fault rocks are formed by mechanical disintegration of the rocks that are displaced along the fault. Depending on the lithology of the fault-dissected rocks, different rocks are formed, e.g. cataclastic gouge or clay smear (Fischer & Knipe 1998).

Clayey substance smeared along the fault plane is a key mechanism that establishes a barrier to the migration of fluids in the rock mass (Fig. 2.1).

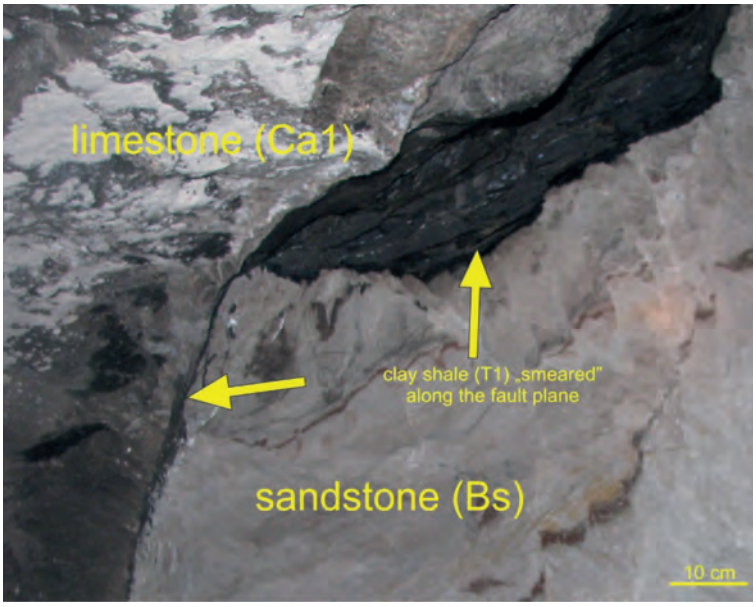


Fig. 2.1. Illustrative fault plane covered with clay smear – copper shale (T1). Zechstein bottom, Fore-Sudetic Monocline

Usually, a fault seal analysis is made for the intervals of alternating reservoir (sandstones, limestones) and sealing rocks (claystones, clay shales). The analysed interval of prospective unconventional oil and gas accumulations generally has a homogenous lithology in the form of claystones and mudstones with poor reservoir properties. These intervals display good sealing characteristics. Hydraulically fractured interval, turned into reservoir level by establishing a network of induced fractures, is an exception.

Faults that dissect the zone of induced fracture propagation represent a potential risk with regard to migration of reservoir fluids. A preliminary SGR-based fault seal analysis has been made in order to assess the potential risk of reservoir fluid migration.

The analysis was made using the TRIANGLE, part of TrapTester software by Badley Geoscience. The software allows for drafting reservoir and sealing rock superposition diagrams and for estimation of the GDR parameter.

The SGR parameter is calculated and analysed in the diagrams (Fig. 2.2) that are generated by the TRIANGLE based on the volume and thickness of clay horizons in the profile of the well. According to the classification proposed by Yielding et al. (1997), it is reasonable to assume that SGR values lower than 20% (or the ratio < 0.2) indicate the presence of cataclasites in the core of the fault, i.e. the appears to be transmissive. SGR values ranging from 0.2 to 0.6 indicate that the analysed fault is partly sealed. If SGR values are in excess of 0.6 the fault can be considered as sealing (Yielding et al., 1997).

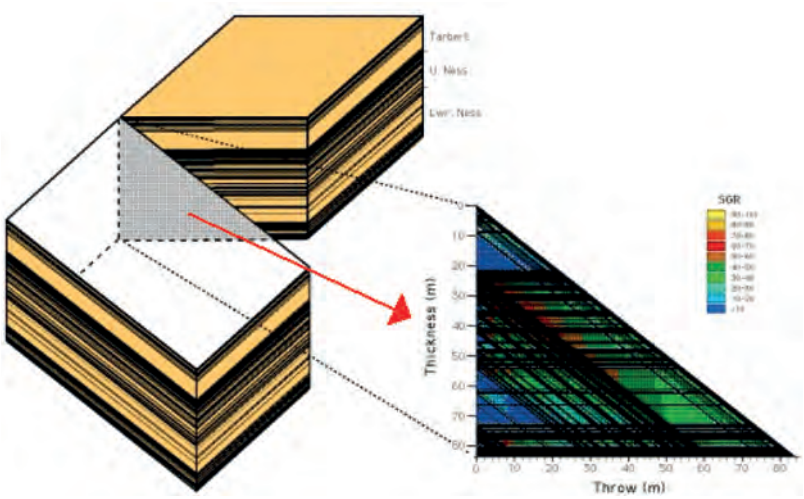


Fig. 2.2. Block diagram (left) representing a fault model and interpretation triangle (right) showing superposition of reservoir and sealing beds with SGR calculated (Badley Geoscience training materials)

Black horizontal fields shown on Fig. 2.2 denote upthrown clayey beds, while transverse black fields denote downthrown clayey beds. Block diagram colours denote changes in SGR values that inform of fault sealing with regard to the distribution of the clay fraction along the fault's plane.

Data provided by the Operators were not always sufficient for delivery of basic fault seal studies. Current logging and seismic data, supported by laboratory tests of core samples and an in-depth structural interpretation would enable a fault sealing estimation.

2.1.3 Assessment of hydrogeological conditions

Hydrogeological conditions prevailing in particular test site areas were first assessed by desktop studies, subsequently supplemented with field surveys (hydrogeological mapping).

Desktop assessment was based on pre-existing materials in paper, electronic and digital formats and on information provided by the Operators.

Field surveys contributed the details of water table in the analysed aquifers.

The collected and analysed pre-existing materials included:

- cartographic studies (Hydrogeological Map of Poland, scale 1:50 000 – top aquifer, commercial aquifers; Detailed Geological Map of Poland, scale 1:50 000; Map of Groundwater Sensitivity to Pollution, scale 1:500 000 and other maps),

- regional documentations e.g. (MA documentations),
- information about hydrogeological objects (Central Hydrogeological Databank),
- groundwater monitoring data,
- data sheets of uniform parts of groundwater bodies,
- information on facilities that have an effect on the status of ground and surface waters,
- Maps of Poland's hydrogeological regions.

An investigation into aquifer occurrence conditions, groundwater dynamics (flow directions) and a new count of hydrogeologic wells producing water from specific aquifers enabled to develop initial concept and design monitoring at test sites.

New hydrogeological cross-sections have been drafted and existing ones supplemented on the basis of the assessment of hydrogeological conditions.

Current data provided by the Operators contributed to the knowledge of hydrogeological conditions. Information on drilled wells or piezometers made by the Operators for the purposes of drill site operations (e.g. geological profiles, groundwater table data) were the key inputs to the hydrogeological analysis and cross-sections.

Tabulation of the collected data enabled the development of the numerical modelling concept, as required for the determination of the hydrogeological processes.

It should be noted that the test sites varied significantly in terms of investigation into hydrogeological conditions, due to a varying accessibility of pre-existing materials and the extent of data handed over by the Operators.

2.1.4 Environmental assessment

A comprehensive overview of the test sites includes the determination of environmental, spatial and socioeconomic conditions that prevail in the proximity of the drill sites.

Geoenvironmental Map of Poland (scale 1:50 000), including explanations thereto, was the key source of geoenvironmental data. Sheets Dzierzgoń, Lębork, Łęczyce, Nielisz, Sawin, Siedliszcze, Skarszewy, Sławoszyno, Stężyca were used. Explanations to the map provided information about landscape, environmentally valuable areas, climate and land management.

Geological and geological-engineering documentations of mineral deposits and projects developed in the neighbourhood of the analysed sites were obtained from National Geological Archives. Also the MIDAS database of mineral resources was consulted.

Available on-line strategic documents of local governments (commune and district levels): environmental protection programmes, studies of spatial development conditions and directions, were used. These documents vary in terms of availability, updating and scope of information contained therein.

Acquired data have been verified and updated using the Local Databank of Central Statistical Office (BDL GUS), which contains a wealth of useful information on: municipal economy, environmental protection, population and economic situation presented by communes and districts.

Furthermore, scientific publications (including papers on physiographic regions of Poland, climate in test site regions, ECONET Netework) along with documents made available by the Operators (including: environmental impact assessment reports, as appended to concession applications, environmental decisions, etc.

2.2 Land surface changes

Land surface changes have been investigated on two test sites in order to determine:

- drill site impact on a quantitative evaluation of the magnitude of changes in land morphology and landscape – within the Wysin test site,
- hydraulic fracture stimulation impact on the development of mass movements in an escarpment located at the eastern boundary of the Stare Miasto drill site.

High resolution terrestrial laser scanning (LiDAR) was used in both cases. Baseline status was established prior to the beginning of exploration works using RIEGL VZ-400 scanner, laser beam widths

of 0.04° and 0.08° (at Wysin site only), corrected for altitude (atmospheric pressure) and ambient air humidity.

A comparative survey has not been made at the Wysin site on suspension of work and rigging down operations, as the recorded changes are not final since the Operator is planning to resume exploration at Wysin in the future.

A survey intended to detect any potential land (slope) deformation has been made at the Stare Miasto site after three weeks of hydraulic fracture stimulation treatment. In order to make the survey as accurate as possible and maximize the coverage, scanner measurements were made from ten sequential locations.

A digital terrain model (DTM) was developed by comparing the land surface obtained from two successive DTM's (two surveying rounds). The generated DTM image was analysed using the method of normal vectors.

Spatial analysis was based on point clouds and DTM models (including elevation models) in the form of triangular irregular networks (TIN), as well as DTM and point clouds combined. Point data describe a complete set of all data collected in the field. Vegetation and various objects other than the ground were also described using the cloud of points. An averaged GRID network with an interval of 5 cm was used to enhance visualization.

Terrestrial laser scanning is a well established land surveying method that provides quasi-continuous topographic information for accurate and precise terrain imaging. Since the beginning of the 21st century TLS is increasingly used in remote sensing to analyse changes based on sets of point coordinates in a three-dimensional space, as an alternative to photogrammetry (and conventional la nd surveying tools). A major advantage of laser scanning is the possibility to record, detect and monitor terrain deformations (e.g. Girardeau-Montaut, 2005, Tsakiri et al., 2006, Monserrat & Crosetto, 2007, Buckley et al., 2008).

Besides vegetation cover, surveying accuracy is affected by meteorological factors, such as cloudiness. TLS cannot be used during atmospheric precipitation. It is recommended to perform imaging at low wind speeds and above-zero temperatures. The velocity of electromagnetic wave propagation is also affected by altitude (atmospheric pressure) and ambient humidity that should be corrected for during the measurement.

2.3 Noise

Noise level measurements are made to determine the nuisances to the local residents from a specific activity. Regulatory standards use the notion of equivalent noise level, i.e. continuous noise level expressed in decibels which has the same effect as exposure to actual variable noise over the same period of time. The only way to establish the equivalent noise level is to monitor continuously the actual noise level so as to determine the value adopted by regulatory standards: the equivalent noise level $L_{aeq,T}$ in averaging time T.

In order to determine the level of noise prevailing at the test sites, the sound should be measured simultaneously at source and in residential areas. Consequently, noise measurement had been made in two locations: at the sound source (near the drill site) and in a residential area (in the proximity of the nearest buildings).

Permissible noise levels in the environment are specified by Minister's of Environment Ordinance of 14 June 2007 on *the permissible noise levels in the environment* (Journal of Laws No. 120, Item 826, as amended).

Equivalent daytime noise level $L_{Aeq\ D}$ (understood as the period of time from 6:00 AM to 10:00 PM) refers to the 8 consecutive least favourable daytime hours, while equivalent night-time noise level $L_{Aeq\ D}$ (understood as the period of time from 10:00 PM to 6:00 AM) refers to the 1 least favourable night-time hour. Permissible noise levels are contingent on particular land allocation under the local planning and zoning scheme. Since, such schemes are not available for the test site areas, permissible noise levels for "farmstead buildings", equal to 55 dB and 45 dB (for daytime and night-time respectively) have been adopted in this study.

Noise level expressed as equivalent sound level were performed using two DSA-50 digital sound recording analysers manufactured by SONOPAN, holding valid calibration certificates, i.e. Certificate

No. 315/OUMI-6/12/01 of 3 September 2012 – Class 1 for DSA-50, serial number 357/2012, and Certificate No. 315/OUMI-6/12/02 of 3 September 2012 – Class 1 for DSA-50, serial number 358/2012. A hand-held IM-10 (Class 2) sound meter had been used till September 2012.

Reading accuracy has been periodically inspected using a homologated KA-50 Acoustic Calibrator, serial number 436/12, Certificate No. 315/OUMI-6/12/04 of 3 September 2012 – Class 1.

Noise measurements made at specific stages of Operators' activities are shown in the Table 2.1.

Depending on actual conditions, recording time ranged from 24 to 360 hours. One of the recording units was placed at the drill site and the other one in the proximity of the most noise-exposed house in a vandalism and theft-secure location (except for Wysin and Zawada sites).

Table 2.1. Noise measurement schedules

Test Site	Noise measurements				
	Initial status (prior to drill site development	As-found status (drill site operations)	Drilling operations	Hydraulic fracture stimulation	On completion of Operator's activities
Lubocino		✓	✓	✓	✓
Stare Miasto		✓		✓	✓
Syczyn		✓		✓	
Wysin	✓		✓		
Zawada	✓		✓	✓	
Gapowo		✓	✓	✓	

During the measurements the microphones equipped in so-called "all-weather hoods" were placed on 4-metre high masts, and the meters were placed in special cases with additional high-capacity batteries. The cases also protected the meters from the elements, moisture in particular.

2.4 Ambient air

Ambient air pollution was determined according to the Minister's of Environment Ordinance of 26 January 2010 on reference values for certain airborne substances (2010 Journal of Laws No. 16, Item 87).

Compounds of which concentrations may potentially increase in the air as a result of drill site operations have been selected from the list attached as Appendix 1 to the above Ordinance for testing in air samples:

- sulphur dioxide,
- total nitrogen oxides converted to NO_2,
- methane,
- total aliphatic C_2–C_{12} hydrocarbons,
- total volatile organic compounds (VOC) converted to methane (total VOC describes the presence of airborne compounds that are of anthropogenic and biogenic origin),
- benzene,
- total BTEX (a mixture of monoaromatics: benzene, toluene, ethylbenzene, styrene and xylene isomers).

Ambient air sampling and airborne particulate tests made during specific stages of Operators' activities are shown in Table 2.2 and Table 2.3, respectively.

Airborne particulate tests were made 1.5 m above the ground and other substances had been tested in the range of 0.5 to 1.0 m above the ground.

Samples for the determination of SO_2 and NO_x were collected by aspirating 60 dm^3 of the tested air through gas washers filled with 25 ml of 0.1M NaOH and 3% hydrogen peroxide solution. Samples for

the determination of benzene and BTEX were collected by aspirating 1 dm^3 of the tested air through sorption tubes filled with Tenax TA 30–60 mesh sorbent. Samples for determination of methane, hydrocarbons C_2–C_{12} and total VOC were taken by aspirating the tested air into tedlar bags.

During the sampling, sulphur dioxide and nitrogen oxides have been oxidized to sulphates and nitrates, respectively. Sulphates and nitrates were determined using ion chromatography. Methane gas concentrations were determined by gas chromatography and C_2–C_{12} aliphatic hydrocarbons by gas chromatography coupled with thermal desorption (GCTD). Samples of 300 cm^3 of the tested air were aspirated from the tedlar bags through sorption tubes filled with two layers of adsorbents: Tenax TA 30/60 mesh and Carbosieve S III 80/100 mesh. Sorption tubes with the adsorbed analytes were transferred into a desorber where the analytes were thermally desorbed and then carried to the chromatographic column in the stream of carrier gas. Volatile organic compounds (VOC), expressed as methane, were determined by gas chromatography, while benzene and total BTEX using gas chromatography coupled with thermal desorption (GCTD).

Table 2.2. Ambient air sampling schedule

Test site	Ambient air sampling					
	Initial status (prior to drill site development	As-found status (drill site operations)	Drilling operations	Hydraulic fracture stimulation	Gas tests	On completion of Operator's activities
Lubocino			✓	✓	✓	✓
Stare Miasto			✓	✓		✓
Syczyn		✓		✓		
Wysin	✓		✓			
Zawada	✓		✓	✓		
Łebień	N/A*					
Gapowo		✓	✓	✓	✓	✓

* N/A: not applicable, a pre-existing survey continued

Table 2.3. Dustiness testing

Test site	Dustiness tests					
	Initial status (prior to drill site development	As-found status (drill site operations)	Drilling operations	Hydraulic fracture stimulation	Gas tests	On completion of Operator's activities
Lubocino			✓		✓	
Stare Miasto						
Syczyn			✓	✓		
Wysin			✓			
Zawada	✓			✓		
Łebień	N/A*					
Gapowo		✓	✓	✓	✓	✓

* N/A: not applicable, follow-up of a pre-existing survey

Airborne particulates were determined using the filtration-weighing method, according to the PN-91/Z-04030/05 Standard. The air (0.7 m^3) was aspirated with aspirator through a polypropylene filter at a rate of 35 dm^3/min for 20 minutes. The total weight of dust retained at the test filter was calculated as the difference between the filter weight before and after sampling. Prior to each weighing, the filter has been conditioned in an desiccator over KOH. The content of the total particles was expressed as µg/m^3. Sensitivity thresholds of the test were 200 µg/m^3 and 40 µg/m^3 at initial status determination/drilling operations and hydraulic fracture stimulation, respectively.

Test results were compared with the values of reference, as set by Environment Minister's Ordinance of 26 January 2010 *on the values of reference for certain airborne substances*, 2010 Journal of Laws No. 16, Item 87. In the case of suspended particles, the Ordinance specifies reference values for the PM10 dust. As the content of the PM10 dust may not be higher than the total content, the application of the PM10 reference value to the test results obtained with the method used should be considered as sound and acceptable.

2.5 Soil

2.5.1 Soil tests

Soil tests made at the test sites included: sampling for chemical tests and (on some of the sites) tests using a SL probe intended to determine a relative degree of soil compaction before and after drill site operations.

The scope of tests varied from one site to another depending on Operators' work schedules.

Normally, soil sampling involved collecting with a sampler an averaged sample from 9 points within a square of 2 x 2 m every 1 m. The only exceptions are: sampling at the reclaimed Stare Miasto site – soil samples have been collected at depths ranging from approx. 20 to 40 cm below the ground level, and sampling at the Łebień site (depths of 0.2 to 0.3 m below the ground level. Soil samples were collected using a manually-operated Eijkelkamp drilling set.

At initial status tests, sampling locations were designated in the planned drill site area (Wysin and Zawada test sites). Moreover, soil samples had been collected following an emergency situation at the Stare Miasto drill site (fracturing fluid spill through the flare). In the latter case, sampling points were contingent on emergency location. At Łebień test site, samples had been collected in the proximity of the fracturing fluid handling location (fluid transfer from an earthen tank to tank trucks.

Soil tests made at particular test sites during specific stages of Operators' activities are shown in the Table 2.4.

Table 2.4. Soil testing schedule

Test site	Soil samples tested					
	Initial status (prior to drill site development	As-found status (drill site operations)	On drilling completion	Hydraulic fracture stimulation	On completion of Operator's activities	After 1–2 years of hydraulic fracture stimulation
Lubocino	–	–	–	–	–	–
Stare Miasto	–	–	–	4	–	6
Syczyn	–	–	–	–	–	–
Wysin	3	–	–	–	–	–
Zawada	3	–	–	–	–	–
Łebień	–	–	–	–	–	5
Gapowo	–	–	–	–	–	–

Hydrocarbon compounds were determined in all soil samples at AGH Laboratory (according to Polish Standard PN-C-04565-01:1982 and German DIN 38409 Standard). Moisture contents were first determined in the soil samples. Subsequently, approx. 3 grams of a raw sample were mixed vigorously with wide-porous silica gel in order to remove moisture from the sample. Then 10 cm^3 of tetrachloroethylene were added to the prepared sample which had been ultrasound treated to release the hydrocarbon compounds, as adsorbed by the soil sorption complex. The next step involved a separation of the solid and liquid phases with a Nutche filter. Absorption spectra have been determined in the obtained solution within a wavenumber range of 2900 to 3150 cm^{-1}. The contents of aromatic and aliphatic hydrocarbons, mineral oil (C_{12}–C_{35}) and gasoline (C_6–C_{12}) were determined based on the height of absorption bands from stretching vibrations of CH_2, CH_3 and $C_{ar}H$ groups.

Soil samples collected at the Łebień site were tested at the AGH Laboratory for:

- specific electrolytic conductivity (SEC) – determined conductometrically (water extract, 1:5 substrate to water proportion, according to PN-EN 13652),
- anionic surfactants (AS) – determined by continuous flow (CFA) spectrophotometry, based on PN-EN 903:2002,
- total organic carbon (TOC) – by infrared spectrophotometry (IR),
- Fe, Mn, B, Ba, Na, Ca, K – by atomic absorption spectrometry (AAS),
- Cl, Br – using the Mohr argentometric method (water extract, 1:5 substrate to water proportion, according to PN-EN 13652),
- NO_3 – a photometric method based on PN-82/C-04576.09 (water extract, 1:5 substrate to water proportion, according to PN-EN 13652),
- NH_4 – method based on PN-75/C-04576,
- phenols (phenolic index) – a spectrophotometric method based on PN-ISO 6439:1994,
- gasolines C_6–C_{12}, mineral oils C_{12}–C_{35}, mineral oils (index) C_{10}–C_{40} – by gas chromatography, based on the Polish Standard PN-C-04565-01:1982 and on the DIN 38409 German Standard.

In addition, soil samples collected at the Stare Miasto site following a drill site emergency event have been tested by District Agricultural Chemistry Station for:

- the contents of particular mineral fractions, according to the PB 40 procedure ed. 3 of 14 February 2011,
- humus content, according to the PB 01 procedure, ed. 4 of 15 October 2009,
- the contents of K^+, Na^+, Ca^{++}i Mg^{++} ions and humic acids, according to the methodology developed by the Puławy-based IUNG Institute,
- the contents of nutritional components: phosphorus, potassium and magnesium, according to the following standards: PN-R-04023:1996, PN-R-04022:1996 + Az 1:2002 and PN-R-04020:1994 + Az 1:2004,
- pH, according to the procedures PB 07 ed. 7 of 15 October 2009 and PB 31 ed. 4 of 15 October 2009.

Tests made with a SL probe were intended to check whether long-term loads from the drilling service facilities or soil stored in the heaps have had an effect on subsoil density in the area under the load. The probe has been hammered into the ground to a specific depth with percussion blows counted for each 10 cm of depth. Results were analysed by comparing the number of percussion blows in the same location before and after loading. Unfortunately, the method could not be used to a full extent due the status of operations on particular test sites. Initial status was determined for Wysin and Zawada test sites only. At Stare Miasto test site, comparative soil compaction studies had been carried out on site reclamation with the status of adjacent farmland as reference.

2.5.2 Soil gas – hydrocarbon components

Atmogeochemical survey of the initial status was intended to determine the natural near-surface distribution field for soil gas concentrations of light hydrocarbons and carbon dioxide in the area of the geological work site. Once known, the field would enable the tracking of potential changes caused by soil pollution with oil derivatives from the ground surface or with gas migrating upwards from penetrated geological formations, for example along the well casing walls. Unfortunately, only in two locations (Wysin and Zawada) the survey could be made for the initial status. In other test sites, soil gas was tested for concentrations of hydrocarbons at various stages of geological works delivered at

the drill site. It was assumed, however, that the first testing round represents the status of reference with regard to subsequent tests made on completion of the analysed stages of exploration. Top soil was sampled for the gas tests considering the local topography, site development patterns, access restrictions and, if technically justified, collection of two or more samples along the vertical projection of the directional well curvature on the ground surface.

Atmogeochemical sampling has been delivered using the apparatus and methodology developed by the Faculty of Energy Resources, AGH University of Science and Technology in Krakow (Dzieniewicz, Sechman, 2002). Soil gas was sampled from a depth of approx. 1.2 m with a special probe and a gas-tight syringe. In light of experimental tests (Dzieniewicz et al., 1978, 1985; Sechman, 2006) and international subject-matter literature, the sampling depth applied is considered as the most optimal. On the one hand, any significant effect of external factor is eliminated and on the other – the top soil is investigated. Testing approach and methodology allows for collecting sterile representative samples, while eliminating any interference from the atmosphere.

Soil gas samplling points were located in the field using topographic background maps, azimuths and distances established with GPS Oregon 550t by Garmin. Coordinates (according to the 1992 PUWG system) were determined for each sampling point. Test grid location was established considering drill site development arrangements and access restrictions.

Two testing rounds had been performed at each test site: one for the initial or as-found status and the other on completion of hydraulic fracture stimulation by the Operators. The Wysin test site is the only exception, as having drilled the vertical well the Operator suspended geological work under the programme. In consultation with the Contracting Authority the decision was made to refrain from studies on the soil gas distribution field of light hydrocarbons and carbon dioxide. Instead, only concentrations of methane under the drill site sheet lining have been determined.

Due to high hydrocarbons concentrations detected in the first testing round at the Syczyn test site, an additional testing round has been delivered on completion of the Syczyn OU-2K directional well. In addition, Syczyn and Zawada were tested after two years of gas tests that followed well stimulation, including hydraulic fracturing jobs.

Soil gas tests made at particular test sites during specific stages of Operators' activities are shown in the Table 2.5.

Prior to soil gas sampling, the probe was each time purified from atmospheric air and potential contaminants. To this end, prior to inserting into the top soil, the probe had been repeatedly purged using a sampling syringe of 100 ml. Since purging operations have been performed in immediate proximity of the sampling location, the air injected to the probe may include potential emanation of the tested components that have been released to the atmosphere in that region. Subsequently, the probe was inserted to the planned sampling depth. A partial vacuum induced by the syringe in the probe-syringe system enabled aspiration of the gas that filled rock medium voids. Sample volume was set at 100 ml.

Table 2.5. Schedule of soil gas testing for hydrocarbons

Test site	Soil gas samples tested					
	Initial status (prior to drill site development	As-found status (drill site operations)	On drilling completion	Hydraulic fracture stimulation	On completion of Operator's activiaties	After 1–2 years of hydraulic fracture stimulation
1	2	3	4	5	6	7
Lubocino	–	25	–	–	25	–
Stare Miasto	–	23	–	–	23	–
Syczyn	–	25	36	–	53	53
Wysin	23	–	10*	–	–	–
Zawada	20	–	–	–	25	51

1	2	3	4	5	6	7
Łebień	–	–	–	–	–	16
Gapowo	–	20	–	–	20	–

* methane concentration only

The collected soil gas samples were transferred from the syringe to a container (small bottle) filled with chemically pure sodium chloride solution to top. By equalizing the pressure, an injection needle inserted through a rubber membrane of the plug displaced excess brine water which was replaced by the gas sample. The volumes of the sample and of the bottle allowed to leave a portion of the solution inside the bottle. This preserves sterility of the sample container and its tightness during the transport to the laboratory (the container was placed upside down). Moreover, by hindering the solubility of gases it simultaneously allowed an observation of the filling processes in the field and when taking the gas sample in the laboratory for chromatographic determinations (Dzieniewicz, Sechman, 2001, 2002).

Molecular compositions of the gas samples were determined by gas chromatography at the Department of Fossil Fuels, AGH University of Science and Technology in Krakow.

The collected gas samples were tested for the presence of methane and its higher homologues (ethane, propane, i-butane, n-butane, neo-pentane, i-pentane, n-pentane), gaseous alkenes (ethylene, propylene, 1-butene), helium, hydrogen and carbon dioxide. That range of chemical testing was required in order to assess the nature of emanation sources and establish reasons behind their occurrence in the soil gas (upward migration from oil and gas accumulations, recent biochemical processes, anthropogenic pollution).

The collected samples were tested using gas chromatography with flame-ionization and thermal conductivity detectors. GC 8160 apparatus by FISONS Instruments was used to determine the contents of hydrocarbons with an accuracy of up to 0.005 ppm at the following operating parameters:

- a 1.3 m-long metal column filled with ActivatedAlumina (mesh 100/120),
- carrier gas – helium (60 ml/min),
- working gases from generators: hydrogen (26 ml/min), air (300 ml/min),
- preset thermostat temperature: 80°C – 3 min, increase rate: 80°C to 200°C (20°C/min), 200°C – 3 min,
- FID detector temperature – 270°C,
- injection chamber temperature – 100°C,
- volume of the injected sample – 2 ml.

Samples were injected manually using a gas-tight syringe. Prior to and after each batch (10–15 samples) standard mixtures were injected to calibrate or, if necessary recalibrate the analyser.

Helium, hydrogen and carbon dioxide were determined using CARLO ERBA Instruments analyser at the following operating parameters:

- a 2.5 m-long metal column filled with 5A molecular sieves (for helium and hydrogen) and a porous polymer (for carbon dioxide),
- carrier gas – argon (30 ml/min),
- thermostat temperature – 65°C – constant,
- TCD detector temperature (base – 60°C, fibres – 180°C),
- volume of the analysed sample – 2 ml (using a ten-way VALCO automatic dispensing valve).

Samples were injected using a ten-way VALCO automatic dispensing valve.

Chromatograms were checked for quality using certified SUPELCO and ALLTECH calibration gases. At the assumed analyser operating parameters, the following times of retention were obtained for the analysed components:

- methane: 0.66 min
- ethane: 1.32 min
- ethylene: 1.97 min
- propane: 3.43 min
- propylene: 5.20 min
- i-butane: 6.01 min
- n-butane: 6.45 min

- 1-butene: 7.80 min
- neo-pentane: 8.55 min
- i-pentane: 8.85 min
- n-pentane: 9.02 min
- helium: 1.59 min
- hydrogen: 1.74 min
- carbon dioxide: 8.97 min.

Quantitative tests were based on known concentrations of particular components of calibration mixtures an made using external standard method.

At external standardization, the result is obtained by comparing the peaks of the analysed sample with corresponding peaks of the calibration sample. The sample and a standard mixture of known composition are analysed in the same conditions. Since flame-ionization detector's signal from the standard (y_{wz}) of known concentration (x_{wz}) and from the sample (y_{pr}) is linear, the sample's concentration (x_{pr}) is calculated using the following formula (Cowper, DeRose, 1988):

$$x_{pr} = \frac{x_{wz} \times y_{pr}}{y_{wz}}$$

PeakSimple integration software was used for digital processing and interpretation of chromatograms. FID detector's detection threshold is equal to 0.005 ppm for hydrocarbons. TCD detector's detection threshold for helium and hydrogen is 0.001 vol% and 0.01 vol% for carbon dioxide.

The determinations were checked for quality during the analysis. The checks involved repeat tests of samples with higher concentrations of methane and its homologues. Moreover, analyser performance was routinely checked by control injections of calibration mixtures each time after approx. 10 consecutive determinations.

The concentrations of gas constituents in the analysed soil gas samples have been tabulated in the order of gas homologues of the paraffin series – alkanes (methane, ethane, propane, i-butane, n-butane, neo-pentane, i-pentane, n-pentane), gaseous unsaturated hydrocarbons – alkenes (ethylene, propylene, 1-butene), helium, hydrogen and carbon dioxide. Moreover, total micro-concentration of C_2–C_5 alkanes and total C_2–C_4 alkenes were presented in separate columns, so as to facilitate interpretation of results. In addition, $C_1/\sum(C_2–C_5)$ ratios were shown as they allow for a preliminary assessment of hydrocarbons for the source(s) of their origin.

Minimum and maximum values, arithmetic mean, standard deviation, median, and the share of a given component above the detector's threshold of detection in the total population of the collected samples were presented to enable an evaluation of the nature of the concentrations and of the coefficient sets. Concentrations of methane, total C_2–C_5 alkanes, total C_2–C_4 alkenes and carbon dioxide are also presented graphically. Concentration changes are presented either as maps of concentration distribution or in the form of circles of diverse colours and sizes. Mapped data have been kriging-interpolated. Distribution is shown as a circle if the points of measurement are located along the profiles or around a sheet lined and concrete slab covered drill site. In that case concentrations are most frequently presented by dividing the sets of measured data into the following sub-sets: from the minimum or detection threshold to the median, and then from median to each order of magnitude up to the maximum value boundary.

Methane and carbon dioxide tests for the composition of stable carbon isotopes

The tests have been made in an attempt to establish the origin of soil gas hydrocarbons in the shale gas exploration drilling regions. Establishing the origin would enable to determine whether elevated concentrations of these compounds, found especially at the Syczyn site, but also at Lubocino and Zawada, are caused by upward migration of gas from penetrated geological formations, i.e. derive directly from drilling operations. Isotopic ratios determined in the soil gas samples were compared to the results of analogous tests of reservoir gas samples collected from Lubocino-2H, Zwierzyniec-1 and Syczyn OU-2K wells. Results of these tests are a value of reference to any potential concentration increases in the future, of which origin also will have to be established.

The number of isotopic ratio determinations in particular locations is shown in the Table 2.6.

Table 2.6. Schedule of soil gas tests for isotopic composition

Test site	Tests for isotopic composition of soil gas hydrocarbons					
	Initial status (prior to drill site development	As-found status (drill site operations)	On drilling completion	Hydraulic fracture stimulation	On completion of Operator's activities	After 1–2 years of hydraulic fracture stimulation
Lubocino	–	2	–	–	–	–
Stare Miasto	–	1	–	–	1	–
Syczyn	–	2	4	–	3	4
Wysin	–	–	–	–	–	–
Zawada	–	–	–	–	-	2
Łebień	–	–	–	–	-	2
Gapowo	–	–	-–	–	–	–

There are two stable isotopes of carbon (^{13}C and ^{12}C) that differ by the mass of a single neutron in the nucleus. The ratio of ^{13}C i ^{12}C occurrence in the environment is equal to approx. 1:90, bringing atomic weight of carbon to 12.011. The ratio of stable carbon isotopes is determined by mass spectrometry and expressed as $\delta^{13}C$, which is the quotient of the difference between isotopic ratios of the sample and the PDB standard and the isotopic ratio of the PDB standard:

$$\delta^{13}C = \frac{^{13}C/^{12}C_{sample} - {}^{13}C/^{12}C_{PDB}}{^{13}C/^{12}C_{PDB}} 1000\ (‰)$$

Methane and carbon dioxide tests for carbon isotopes were made by "on-line" method using Finnigan Delta Plus mass spectrometer coupled to Hewlett Packard gas chromatograph via GC Combustion III unit.

A gas sample is dispensed to the injection chamber of the gas chromatograph. Gas constituents are separated in the chromatographic column and transported by carrier gas (helium) to the furnace where methane is incinerated at 980°C with carbon dioxide and water as combustion products. The latter flow to the coupler unit where carbon dioxide is separated from other constituents. Individual constituents are then transferred (in the order of elution from the chromatographic column) to the analytic system of the mass spectrometer where they are measured. The accuracy of stable carbon isotope determination, including sample preparation and calibration with standard, is equal to $\pm$0,2‰.

There are two stable isotopes of hydrogen ^{1}H (prot) and D = ^{2}H (deuter). Average natural abundances of ^{1}H and ^{2}H are 99.9844% and 0.0156%, respectively. The results of D/H stable hydrogen isotope ratio determinations are expressed as δD rather than absolute values. The δD is the quotient of the difference between isotopic ratios of the sample and the SMOW standard and the isotopic ratio of the SMOW standard:

$$\delta D = \frac{D/H_{sample} - D/H_{SMOW}}{D/H_{SMOW}} 1000\ (‰)$$

The error in the determination of the hydrogen stable isotope ratio is equal to $\pm$ 3‰.

The water produced by methane combustion is transferred to a capillary tube which is then fused. Subsequently, the capillary tube is placed in a special previously vacuumed quartz vessel with zinc and immersed in liquid nitrogen. The capillary tube breaks under the influence of low temperature and releases the water. The vessel with water is placed for two hours in a furnace at 500°C where reduction reaction $H_2O + Zn = ZnO + H_2$ occurs and then is connected to the spectrometer for the measurements.

Field tests for emissions

Emission tests had been carried out at two test sites. Emissions were tested in three selected locations at the Syczyn test site and two locations at the Zawada test site. In both cases the tests were made in July 2014.

A modified method of static chambers was applied in the field tests (Leventhal 1992, Korus et al. 2002, Dzieniewicz et al. 2006, Sechman et al. 2006, Sechman, Dzieniewicz 2009). This is a proprietary method of emission testing with a borehole (Korus et al., 2010). The borehole simulates a disruption of continuous soil mantle, enabling the tests of uncontrolled flow of gas to the enclosed space.

Traditionally applied method of emission measurement at the ground surface (without drilling a borehole) enabled estimation of methane that has not been decomposed by the bacteria before being naturally released to the atmosphere (Etiope & Klusman 2002). It is generally assumed that, depending on environmental conditions, methanotrophic bacteria are most active in the soil to a depth of approx. 0.6 m (Kunicki-Goldfinger 1994). Some scientists consider this zone as a specific "bacterial filter" capable of reducing significantly or even preventing methane release to the atmosphere (Klusman 2005).

The patent-protected emission measurement methodology (Korus et al., 2010), as applied in this study, consists of collecting, in specified time intervals, gas samples inside a closed chamber placed on the ground surface. In this study, a bowl-shaped stainless steel chamber with a capacity of 10.8 dm^3 was used to measure the emission (Fig. 2.3).

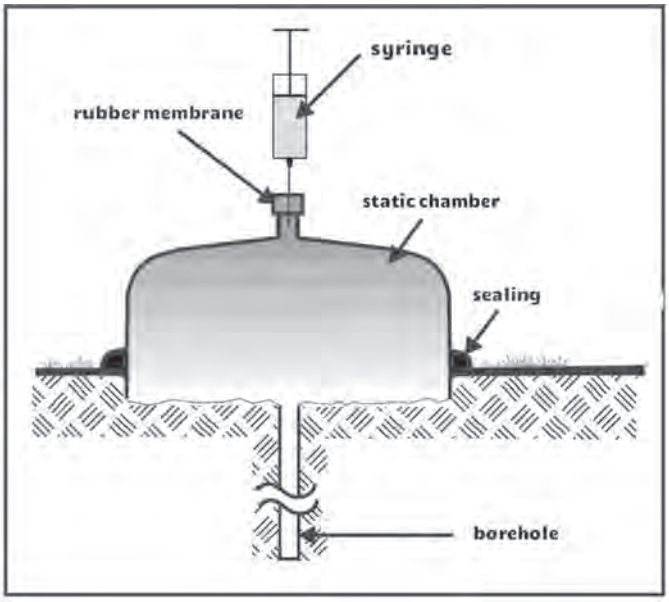


Fig. 2.3. Emission measurement kit (Korus et al., 2010).

The chamber isolated from the atmosphere a circular ground area of 7.1 dm^2. Since the tests were delivered on a slab-reinforced drill site, chamber walls were sealed at the contact with the ground.

An about 1 m-deep borehole has been drilled out with a tube of 10 mm in diameter prior to chamber installation (Fig. 2.3). A cylindrical side surface of 100 cm x 3.14 cm thus established meant an additional emission area which has been considered in the calculations. Subsequently, gas samples of 50 ml each have been collected from the chamber after 5, 15 and 30 minutes from the chamber installation time. Moreover, an atmospheric air sample has been collected above the ground at each site prior to chamber installation. Atmospheric pressure and soil temperature at

the depth of 10 cm have been measured while collecting the samples from the chamber. Once collected, the samples were transferred to containers filled with NaCl solution for subsequent delivery to the laboratory in upside down position. Due to container capacity (approx. 60 ml) some of the brine water remained in the containers providing an additional protection against potential atmospheric interference.

At the Syczyn site, emission was measured at three test points where elevated soil gas methane concentrations were previously found. Methane concentrations in these points amounted to 22.1 vol%, 35.4 vol% and 6.97 vol%, respectively, while carbon dioxide concentrations were 9.26 vol%, 3.26 vol% and 2.48 vol%, respectively. In addition to elevated methane and/or carbon dioxide concentrations, the volume of the soil gas sample collected (100 ml), indicating a good permeability of the soil at the gas sampling depth, was a criterion for the selection of the emission measurement points.

Emission calculation methodology

Methane and carbon dioxide emissions have been calculated using the theoretical assumptions and methodology described in detail by studies on similar measurements made in abandoned coal mining areas (Korus et al., 2002, Dzieniewicz et al., 2006).

Methane and carbon dioxide emissions have been calculated using the following equations (Korus et al., 2002, Dzieniewicz et al., 2006; Sechman & Dzieniewicz, 2009):

$$E^{CH_4} = \frac{V_p}{A} \cdot \frac{M_W \cdot T_0 \cdot p}{M_V \cdot p_0 \cdot (T_0 + t_{gl})} \cdot n^{CH_4} \quad (1)$$

$$E^{CO_2} = \frac{V_p}{A} \cdot \frac{M_W \cdot T_0 \cdot p}{M_V \cdot p_0 \cdot (T_0 + t_{gl})} \cdot n^{CO_2} \quad (2)$$

where:

E^{CH_4} – CH_4 emission ($g \cdot dm^{-2} \cdot min^{-1}$);

E^{CO_2} – CO_2 emission ($g \cdot dm^{-2} \cdot min^{-1}$);

M_W – molecular weight of the gas (for CH_4: $M_W = 16$ g, for CO_2: $M_W = 44$ g);

M_V – volume of 1 mole of the gas at normal conditions ($p_0 = 1013 \cdot 10^2$ Pa, $T_0 = 273$ °K) ($M_V = 22.4$ dm^3);

t_{gl} – soil temperature at the time of measurement (°C), ($T_0 = 273$ °K);

p – atmospheric pressure at the time of measurement (Pa);

V_P/A – a chamber parameter (V_p – volume in dm^3, A – emission area in dm^2);

n^{CH_4}= dc/dt for $t \rightarrow 0$ (CH_4 concentration buildup rate in the chamber (ppm$_*$min^{-1}) based on concentration buildup function);

n^{CO_2}=dc/dt for $t \rightarrow 0$ (CO_2 concentration buildup rate in the chamber (vol%$_*$min^{-1}) based on concentration buildup.

Soil temperature and atmospheric pressure value applied in equations (1) and (2) were the average of measurements made at sampling, considering a small variability of the measured values.

In order to assess the rate of methane concentration changes, linear graphs showing concentration variability with time have been drawn up. A computer-generated linear trend of changes in methane and carbon dioxide concentrations was shown on the graphs. The coefficient of the determination (R^2) and straight line equation were established for the determined trend line. Based on the determined straight line parameters, the rate of methane and carbon dioxide concentration changes (increase or decrease) in the chambers (n^{CH_4}, n^{CO_2}). The calculated changes in methane concentrations are expressed as ppm per minute *(ppm · min^{-1})*, and in the case of carbon dioxide as vol.% per minute *(vol% · min^{-1})*. The results have been presented in a tabular format. Additionally, methane and carbon dioxide emissions (E^{CH_4}, E^{CO_2}), as computed from algorithms (1) and (2), are presented in the tables. Methane emission is expressed as milligrams per square metre per day *(mg · m^{-2} · d^{-1})*, and that of carbon dioxide as grams per square metre per day *(g · m^{-2} · d^{-1})*.

2.5.3 Soil gas – radon

Soil gas tests for radon (^{222}Rn) concentrations have been delivered as close as practicable to the drilling well at Lubocino, Stare Miasto, Syczyn, Wysin and Zawada sites. The measurements were made in two rounds: for the initial or "as found" status and on completion of hydraulic fracture stimulation by the Operators. Wysin test site is the only exception, as the Operator failed to deliver fracture stimulation during the duration of the project.

The measurements of radon (^{222}Rn) concentrations were made primarily in the near-well zone, where any potentially anomalous radon (^{222}Rn) concentrations are most likely to occur, and adjacent areas within a radius of approximately 150 m. A grid of test points with centrally located wellhead was prepared for each of the sites.

Samples were not collected from the near-well zone and some test point locations have been slightly modified at the Stare Miasto site, where drill site sealing with sheet lining and concrete slabs prevented sample collection within the drill site area.

Also at the Syczyn and Zawada test sites, locations and/or the number of specific test points at the final test round (on completion of Operator's activities) have been modified on account of site infrastructure changes (water storage tanks erected at Syczyn, a paved and sealed with sheet lining yard built at Zawada).

Upon completion of vertical exploratory well drilling operations at the Wysin test site, additional control measurements were made prior to taking off the sealing sheet. The tests were intended to check for potential buildup of radon concentrations beneath the impervious lining.

Seasonal and diurnal variations of weather conditions (pressure, air humidity, wind strength, temperature) have an effect on the soil gas concentrations of gases and may potentially distort the readings. Therefore, it was imperative to deliver the second round of measurements in the same season and under similar weather conditions as the first one.

Radon (^{222}Rn) concentrations tests at particular stages of test site operations are shown in the Table 2.7.

Table 2.7. Schedule of tests for radon concentration in the soil gas

Test site	Soil gas radon concentration measurement points		
	Initial status (prior to drill site development)	"As-found" status (drill site in operation)	On completion of Operator's work
Lubocino	–	15	15
Stare Miasto	–	19	19
Syczyn	–	23	23
Wysin	16	–	12
Zawada	30	–	28

Samples were collected with probes squeezed into the ground to a depth of 80 cm. The adopted sampling depth was based on subject-matter literature (Asher-Bolinder et al., 1991) and previous experience from field studies. The depth of 80 cm guarantees that the atmospheric air has no access to the soil gas sampling probe, i.e. that the tested gas comes from the geological basement.

Soil air samples of 150 ml were tested using a portable RADON DETECTOR LUK-3B device. Soil gas sample was transferred with a special syringe to the so-called Lucas Chamber of the device which automatically made the test and processed data with the installed software. Radon concentrations in the soil gas were expressed in kBq/m^3, where 1 becquerel denotes one radioactive atom disintegration during one second.

Measurements of radon (^{222}Rn) concentrations in soil gas require statistical treatment due to a very high variability over a small area, which is due to several factors, including mainly lithology and weath-

er conditions. The computed arithmetic mean was referred to the radon potential classification by Akerblom, 1986: (<10 kBq/m^3: low potential; 10–50 kBq/m^3: average potential; >50 kBq/m^3: high potential). Since Polish legislation does not regulate radon concentrations in soil gas, atmospheric air or other environments, the classification was adopted as a level of reference to the interpretation of measurement results.

2.6 Surface and ground waters

2.6.1 Mapping

The purpose of the mapping was to collect information that is required for the development of a water monitoring concept. The aquatic/soil environment has been assessed and potential changes occurring as a result of hydraulic fracture stimulation and gas tests have been recorded as part of water monitoring.

Mapping involved identification of hydrogeological and hydrological objects that may prove useful for monitoring the status of the aquatic/soil environment and was preceded by sampling of surface and ground waters.

Test site operations were conducted within a radius of 2–5 km from the drilling well. The size of surveyed area was first estimated by desktop studies that preceded field operations.

Desktop studies were intended to investigate geology and hydrogeological conditions in the region of particular test sites and included gathering and analysis of pre-existing materials – see Chapters 2.1.1. and 2.1.3.

Monitoring points for surface (water courses, lakes, retention reservoirs, workings, etc.) and underground waters (groundwater, perched water, top aquifer (TA), commercial aquifers (CA and MCA) have been mapped at the inflow and outflow to/from the drill site area.

The inventory of groundwater monitoring points includes: drilled water wells, hand-dug water wells, sources, drainage wells and environmental research wells (Fig. 2.4).

Fig. 2.4. Illustrative groundwater monitoring points – drilled water wells – Wysin Test Site.

The locations of monitoring points were established using a GPS receiver. All hydrogeological objects identified in the field have been assessed for their suitability to water sampling for physical and chemical tests (accessibility, physical condition of the facilities, current use, scope and degree of usage were taken into account and potential impact from any local sources of pollution was verified).

Information on specific monitoring points was obtained from owners or users during site visits.

The size of the surveyed areas at specific test sites and the number of recorded monitoring points is shown in the Table 2.8.

Table 2.8. The size of the surveyed areas at specific test sites and the number of recorded monitoring points

Test site	Surveyed area – estimated size in km²	Recorded groundwater monitoring points	Recorded surface water monitoring points
Lubocino	12.5	14	5
Stare Miasto	78.5	17	4
Syczyn	78.5	28	-
Wysin	28.0	16	2
Zawada	78.5	15	2
Łebień	12.5	–	–
Gapowo	28.0	16	1

Water table in hand-dug water wells, some drilled water wells and piezometers was established using an electrical hydrogeological whistle (probe attached to electrical wireline). In addition, preliminary tests of water samples were made for: pH, SEC (specific electrolytic conductivity) and temperature.

The datum of points for which geodetic data were not available was established using a topographic map at a scale of 1:10 000. In case of other monitoring points datum data have been taken from as-built documentation. The acquired data and information about the aquifer being produced/investigated are presented for each test site in the table of monitoring points.

Moreover, the approach to drill site drainage (belt ditches, drains and drain tanks) has been documented. The water was sampled from some of the documented points located within the drainage network at Lubocino and Stare Miasto test sites.

2.6.2 Modeling

In order to optimize the monitoring network and establish migration paths of potential pollutants in the aquifer, a digital model of hydrogeological processes (hydrodynamic models and a transport model for the Lubocino test site) was developed for each test site.

Modeling included discretization of the surveyed area and the determination of the model boundaries (some of them extended far beyond the test site area). Moreover, boundary conditions were defined and hydrogeological conditions schematized, a proper computation algorithm was selected and the model was calibrated in order to determine the effective filtration coefficient of the aquifer. The models were developed according to the PUWG-1992 system of coordinates.

Groundwater table datums, which served as reference in the identification process, have been established in the field or from a map of hydroisohypses, as compiled for the purposes of the Hydrogeological Map of Poland at a scale of 1:50 000 (HMP).

The conformity of the hydrodynamic groundwater stream, as established during hydrogeological mapping and of the image of hydroisohypses (HMP) with the computer simulation derived image was the key model calibration criterion.

The groundwater head, as measured or determined on the basis of hydroisohypse maps was compared with that calculated for reference points (target type head). Filtration coefficient has been modified using the PEST module in the process of automatic calibration of the model.

It is generally assumed that standard deviation of differences between field measurements and model-derived values should not exceed 15% of the range of measurements. This value was not exceeded in the analysed cases. Model calibration process showed a satisfactory concordance of calculated and measured data.

MODPATH Module of Groundwater Vistas was used for calculation and visualization of groundwater stream lines and approximate groundwater flow times through the aquifer.

To solve the problem, the path of the current flowing from the drill site has been simulated using the model. To this end, particles have been placed at the drill site and their migration in a time interval of 25 years was analysed, assuming variable effective porosity of the Quaternary aquifer medium. Moreover, in the case of Lubocino test site, time of pollutant migration to the boundaries of the nearest MCA has been analysed.

Effective porosity of the aquifer medium was calculated using an empirical formula that shows the relationships between filtration coefficient and drainage capacity (Bieciński formula), assuming that drainage capacity approximately equals effective porosity (it should be kept in mind that the value is approximate only).

$$\mu = 0{,}117\ k^{1/7}$$

where: k – infiltration coefficient [m/d]

Moreover, the time of (potentially contaminated) water infiltration through the zone of aeration was calculated in addition to modelling in order to estimate groundwater vulnerability to ground surface contamination. Bindeman formula was used in these calculations:

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

where:

V_a water infiltration rate through the zone of aeration,

n_0 effective porosity coefficient,

ω infiltration intensity,

k filtration coefficient.

Percolation rate value from the above formula was used to calculate the time of percolation from ground surface to the aquifer:

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

where:

l – denotes percolation path (aeration zone thickness).

2.6.3 Sampling

Water samples have been collected at selected monitoring points, as established during hydrogeological mapping, to enable an assessment of surface and ground water status in terms of chemistry and to identify potential risks to the aquatic environment.

At each test site, ground and surface water samples have been collected in two or more test rounds. The number of rounds was contingent on the situation actually prevailing in particular test sites. Wysin test site is the exception, as following Operator's decision to cancel the initially planned operations only one test round was completed to establish the initial status (before drill site development).

Depending on the progress of Operators' work, round I was intended to establish the initial status (no drill site operations) or the "as-found" status (drill site in operation).

The number of test rounds effected at particular test sites is shown in the Table 2.9.

Table 2.9. Ground and surface water test rounds at particular test sites

Operation stage	Test site						
	Lubocino	Stare Miasto	Syczyn	Wysin	Zawada	Łebień	Gapowo
Initial status (before drill site development)				Round I	Round I		
As-found status (drill site in operation)	Round I	Round I					Round I
As-found status (horizontal leg drilling)							
Horizontal leg drilling completed	Round II		Round I				
Prior to hydraulic fracture stimulation			Round II		Round II		
During hydraulic fracture stimulation			Round III				
On completion of Operator's activity	Round III	Round II and III	Round IV		Round III		Round II
After 1–2 years of hydraulic fracture stimulation		Round IV	Round V		Round IV	Rounds I, II, III	

Hand-dug wells and some of the drilled water wells (depending on well use patterns) were each time pumped through with in-built or portable pumps. Samples were collected according to the procedures of National Environmental Monitoring[5] surveys.

Exceptionally, the above procedure was not followed:

- if it was impracticable to collect raw water sample due to well completion characteristics (no tap and inability to dismantle the water supply installation), the sample was collected using a single-use discrete tubular tester lowered into the well,
- if it was impracticable to pump the well through and collect samples with a pump (non-completed, abandoned or otherwise inaccessible deep well), the sample was collected using a single-use discrete tubular tester lowered into filter interval of the well,
- if it was impracticable to collect raw water sample due to well completion (no tap), the sample was collected from the nearest operational hydrant,
- if it was impracticable to pump the wells through – sampling the water from test wells (due to well constructions and temporary filter used), the samples were collected using a PE pipe with a non-return valve attached at the bottom.

The number of monitoring points sampled at each test round is shown in the Table 2.10.

Table 2.10. Monitoring points sampled at each test round

Test round	Monitoring points sampled						
	Lubocino	Stare Miasto	Syczyn	Wysin	Zawada	Łebień	Gapowo
1	2	3	4	5	6	7	8
I	19	15	13	12	13	3	12
II	10	8	3	–	2	5	12

[5] http://mjwp.gios.gov.pl/art_metodyka/o-metodyce.html

1	2	3	4	5	6	7	8
III	10	9	2	–	15	5	–
IV	–	12	13	–	2	–	–
V	–	–	4	–	–	–	–

At all test rounds, samples of water from process water tank and drainage tanks (Fig. 2.5) have been collected at the Lubocino test site. Moreover, samples of water from the local drainage network have been collected at the Stare Miasto test site (test rounds I, II and III) in order to assess drill site impact on shallow aquifers and detect potential penetration of contaminants thereto.

Fig. 2.5. Drainage tanks at Lubocino Drill Site.

Samples of water used in fracturing fluid preparation have been collected prior to each hydraulic fracture stimulation job.

Additional samples were collected from selected monitoring points at Stare Miasto test site following an emergency event of flowback fluid spill from the flare, at plug redrilling operations (flowback water return) and gas tests.

At Syczyn test site, two additional test water wells have been drilled and sampled during hydraulic fracture stimulation.

In accordance with groundwater monitoring concept, as presented in the final report on survey at Stare Miasto, Syczyn i Zawada test sites and the Łebien Report ("*Studies on environmental aspects of hydraulic fracture stimulation in Łebień LE-2H well*"), follow-up tests of selected monitoring points have been carried out after 1 or 2 years of hydraulic fracture stimulation date.

At Stare Miasto test site, water samples have been collected at monitoring points that were previously used for the determination of the as-found status of the aquatic/soil environment (surface waters, including a pit pond, groundwater). However, due to the removal of piezometers (at drill site reclamation), monitoring boreholes have been drilled in approximate location of the piezometers to collect groundwater samples from the top aquifer.

Monitoring boreholes have been drilled using a string of ϕ32 mm PE pipes with lost orifice filter (orifice 0.2 mm). The string was squeezed into the hole that was previously drilled using the truck (ISUZU D-MAX) mounted small size WGS-160 WH drilling machine. The samples were collected using a ϕ10 mm PE pipe terminated with on-return valve to laboratory-approved containers. The entire PE string was retrieved on sampling completion. Below the water table the hole was liquidated by collapsing borehole walls and in the aeration zone it was backfilled with cuttings in the order of their retrieval.

At Syczyn test site, due to hydrogeological conditions and considering modelling results, water samples have been collected from two drilled water wells located in the drill site perimeter and from a farmstead well located in immediate drill site neighbourhood on the path of water flow from the drill site, as well as from a source located uphill of the drill site.

At Zawada drill site, due to hydrogeological conditions and considering modelling results, water samples have been collected from two drilled water wells located in the drill site perimeter.

At Łebień drill site, water was sampled from drilled wells, including those located in the site perimeter. Additionally, monitoring wells have been drilled out in immediate proximity of the drill site during the third monitoring round.

Monitoring boreholes have been drilled using a string of ϕ36 mm steel pipes with lost ϕ16 mm PVC filter. The string was vibration squeezed into the hole that was previously drilled using the truck (ISUZU D-MAX) mounted small size WGS-160 WH (Fig. 2.6).

Fig. 2.6. Monitoring well drilling – Łebień Test Site.

Once the target depth reached, the string was pulled up by approx. 0.4 m, rupturing the cone and exposing the filter to enable the flow of water into the borehole. The samples were collected using a ϕ10 mm PE pipe terminated with a non-return valve into laboratory-approved containers.

The entire string was retrieved on sampling completion. Below the water table the hole was liquidated by collapsing borehole walls and in the aeration zone it was backfilled with cuttings in the order of their retrieval.

The following operations were made at ground or surface water sampling points:

- pH measurement – with portable microprocessor-based SP300 pH-meter (manufactured by Slandi),
- specific electrolytic conductivity (SEC) measurement – with portable microprocessor-based Slandi SP300 conductometer,
- temperature measurement – with portable microprocessor-based Slandi SP300 pH-meter,
- measurement of water table depth in the wells and piezometers using an electrical hydrogeological whistle (probe attached to electrical wireline),
- water sampling for laboratory tests for inorganic indicators (anions, cations, TOC, Hg),
- water sampling for laboratory tests for organic indicators,
- water sampling for laboratory tests for gaseous substances (methane gas).

The samples have been collected to containers provided by the laboratories, stored and transported in chilled containers.

All the collected samples were delivered to the Central Chemical Laboratory of PGI-NRI and to the Laboratory of Gdańsk University of Technology.

2.6.4 Laboratory tests

The scope of groundwater tests was the same as that adopted by National Environmental Monitoring[6] for assessments of groundwater chemical status. Water samples were tested by Central Chemical Laboratory of PGI-NRI in Warsaw and the Laboratory of Gdańsk University of Technology.

[6] http://mjwp.gios.gov.pl/art_metodyka/o-metodyce.html

The following tests of water samples were performed by the accredited Central Chemical Laboratory of PGI-NRI[7]:

- the determinations of the physical and chemical indicators: pH (potentiometrically), conductivity (conductometrically), NH_4, total alkalinity, HCO_3, TOC, COD, colour, cyanides, anionic surfactants AS (spectrophotometrically), turbidity (nephelometrically), total dissolved solids (calculated),
- ICP-AES determinations of: B, Ba, Ca, Cr, Fe, K, Mg, Mn, Na, SiO2, Sr, Ti, Zn,
- ICP-MS (Inductively Coupled Plasma Mass Spectrometry) determinations of : Li, Be, Al, V, Co, Ni, Cu, As, Se, Mo, Ag, Cd, Sn, Sb, Tl, Pb, U,
- ionic chromatography determinations of: F, Cl, NO_2, Br, NO_3, HPO_4, SO_4,
- mercury determinations by AAS (atomic absorption spectrometry) – AMA 254 mercury analyser.

The Laboratory of Gdańsk University of Technology made the following determinations of indicators in water samples:

- benzene, total BTEX, methane, total C_2–C_{10}, aliphatic hydrocarbons, tricholoethene, tetrachloroethene (by head space (HS) method with nitrogen as head space gas),
- phenolic index (spectrophotometrically),
- non-ionic detergents (spectrophotometrically),
- anionic detergents (methodology analogous to EPA 425.1),
- oil index, total glycols (ethylene glycol and propylene glycol), total higher aromatic hydrocarbons HAH (gas chromatography),
- benzo(a)pyrene (gas chromatography)

It should be noted that organic indicators were not determined in a majority of surface water samples, while the scope of groundwater determinations varied (full scope for water sampled at the so-called benchmark points and a reduced scope in the case of other samples.

2.7 Process fluids and wastes

2.7.1 Sampling

Depending on technical conditions and process line construction, the following samples were collected at test sites during Operators' activity:

- spent drilling mud,
- solid drilling wastes – cuttings,
- fracturing fluids,
- flowback fluids,
- flowback proppant,
- floback wastes (wastes from flowback water treatment process and solid waste from the coarse separator).

Samples collected at tests sites are presented by number and type in the Table 2.11.

Table 2.11. Collected waste and process fluid samples by number and type

Test site	Type of samples/number of samples					
	Spent drilling mud	Solid drilling waste	Fracturing fluid	Flowback proppant	Flowback fluid	Solid flowback waste
1	2	3	4	5	6	7
Lubocino	2	3	4	1	16	2
Stare Miasto	1	1	1	2	5	–
Syczyn	1	1	5	1	5	3

[7] http://www.pgi.gov.pl/pl/instytut-geologiczny-laboratoria/laboratorium-chemiczne-clch.html

1	2	3	4	5	6	7
Wysin[8]	2	2	–	–	–	–
Zawada	1	1	1	1	4	–
Gapowo	1	1	3	–	6	–

Samples of cuttings from the target formation (Ordovician/Silurian shales) have been collected during drilling operations along with mud samples at the stage of drilling through these formations. At the Wysin test site, additional samples of the penetrated Buntsandstein sandstone formation were collected to verify the hypothesis on elevated radioactivity of that horizon. Cuttings samples were collected at the collective container and/or shale shakers. Drilling mud samples were collected from mud tanks (a closed drilling mud circulation system).

Fracturing and flowback fluid sampling locations were contingent on technical conditions (including the number of fracturing stages and variability of fluid composition), as well as on process line layout.

Proppant samples were collected from the flowback water treatment system. Flowback waste samples were collected at the following locations: vehicle hauling the flowback fluid to the external treatment plant, at the mobile Veolia wastewater treatment facility located in the municipal wastewater treatment plant at Chełm – treated fluid and solid waste (Syczyn test site); coarse separator waste was collected directly at separator cleaning site.

PBI-NRI staff members collected the waste and process fluid samples and delivered them to the laboratories of PGI-NRI, AGH University of Science and Technology and Gdańsk University of Technology for testing.

2.7.2 Laboratory tests

Laboratory tests of drilling mud, cuttings, proppant and solid flowback wastes were intended to investigate their physical and chemical properties, concentrations of organic substances and the contents of natural radioactive isotopes.

Test results made it possible to identify the potential for subsequent management of the wastes or their potential application in processes other than neutralization (e.g. production of building materials). In the case of spent mud and drilling wastes, leachability test results were compared with the criteria for acceptance of wastes for storage at grounds for disposal of hazardous, non-hazardous and inert wastes (according to Economy Minister's Ordinance of 8 January 2013 on the criteria and procedures of acceptance of wastes for storage at disposal grounds intended for a particular type of waste, 2013 Journal of Laws, Item 38). The comparison is purely theoretical, as under existing regulations waste neutralization by storage is possible only by storing them at drilling waste neutralization facilities. Nevertheless, the results of spent mud, drilling waste and proppant tests for natural radioactive isotopes have been compared with the requirements that apply to raw and building materials used in buildings intended for occupation by humans, as specified by Council of Ministers' Ordinance of 2 January 2007 on the requirements concerning the content of natural radioactive isotopes in raw materials and materials used in buildings that are intended for occupation by humans and livestock, in industrial wastes used in construction, and on control of contents of these isotopes – 2007 Journal of Laws No. 4, Item 29.

Sixty four indicators were determined in each sample of the spent mud, drilling waste and solid flowback waste (SFW) and 5 determinations of the content of organic components (hydrocarbons) in each proppant sample.

Al, Ca, Fe, Mg, Na Si, Y and Ti cations were determined using inductively coupled plasma emission spectrophotometer ICP-AES (Perkin Elmer OPTIMA 7300DV), and the remaining cations using inductively coupled plasma mass spectrometer ICP-MS (Perkin Elmer ELAN 6100). Samples were diluted 1000 fold for ICP-MS and 100 fold for ICP-AES determinations. Dilution provides higher limits of detection in the case of particular cations.

[8] A change in Operator's strategy) – hydraulic fracture stimulation cancelled.

Spent mud and drilling waste samples were tested for leachability of substances contained therein. Leachibility tests were carried out according to PN-EN 12457-2:2006. Water extract preparation: single-stage waste leachability test at L/S=10 l/kg dw About 2-5 kg of homogenized waste delivered in a container were collected and a sample for leaching was weighed by quartering so as to represent 100 g of dry matter contained in the sample (with accuracy of 10^{-2}g). Moisture was first determined according to PN-EN 12880:2004. Total moisture was determined by weighing method: a sample of 2 kg (with accuracy of 10^{-2}g) has been dried for several days at 105°C to obtain dry matter. Using this, the amount of the water added has been each time calculated so as to ensure the proportion L/S=10 l/kg dw (±2%). After adding the water, the container with dual-phase content was placed in a shaker-mixer for 24 hours and then the solid phase was separated by decanting or centrifuging (most often both). The supernatant was laboratory tested for all of the scheduled physical and chemical indicators. Concentrations in the solution (mg/dm^3) were recalculated to kg dw of waste.

Fracturing and flowback fluids were laboratory tested for chemical composition, including the content of organics and natural radioactive isotopes. In total, 41 determinations of metal ions and 26 determinations of organics were made, including total hydrocarbons by aliphatics and aromatics, total organic carbon (TOC), dissolved organic carbon (DOC), phenolic index, surfactants and HAH.

At Syczyn test site, flowback waste samples were tested to compare chemical compositions of flowback fluids before and after treatment, as well as to establish the potential for reuse/neutralization of these wastes.

Testing standards and procedures used are presented in the Table 2.12.

Table 2.12. Drilling waste and process fluid testing standards and procedures followed by AGH Laboratory

Item	Basic standard	Parameter – component tested
1	2	3
1	PN-93 Z-15008/02 PN- EN 12880:2004	Total moisture – by weighing method
2	PN-77/G-04528/02 PN-EN 12879:2004	Loss on ignition – by weighing method
3	PB WFIS/KUTh/1:1.02.2013	Concentration of natural radioactive elements ^{40}K, ^{226}Ra, ^{228}Th – by spectrometry – by gamma radiation
4	PN-EN 933-1:2012	Grain size determination – by sieve analysis (mechanical classification)
5	PN-EN 12457-2:2006	Water extract preparation: Single-stage waste leachability test at L/S=10l/kg dw
6	PN-EN27888:1999	Electrical conductivity – by conductometry
7	PN-EN 13656:2002	Solid sample dissolution for ICP-MS tests
8	PN-EN ISO 17294-1:2007 PN-EN ISO 17294-2:2006	Determination of metal concentrations – by inductively couples plasma mass spectrometry (ICP-MS)
9	PN-EN 12457-4:2006	Determination of total dissolved solids (TDS) – by weighing method
10	PN-EN ISO 9963-1:2001	Acid neutralization capacity (ANC) – by titration
11	PN-EN ISO 9963-1:2001	Determination of HCO_3^- i CO_3^{2-} ions – by titration
12	PN-EN 12457-4:2006	Determination of Cl^- ions – by titration

1	2	3
13	PN-ISO 6059:1999	Determination of Ca^{2+} i Mg^{2+} ions – by titration
14	PN-ISO 9280:2002	Determination of SO_4^{2-} ions – by weighing method
15	PN-ISO 1690:2000	Determination of silica content – by weighing method

Flowback fluids (FBF) were tested at the Central Chemical Laboratory of PGI-NRI for anionic and cationic components. Due to high concentrations of the organic matrix, samples were diluted 1000 fold for ICP-MS (inductively coupled plasma mass spectrometry) and 100 fold for ICP-AES determinations. Dilution provides higher limits of detection for particular parameters. Testing procedures used are presented in the Table 2.13.

Table 2.13. CCL PGI-NRI laboratory procedures for flowback fluid testing

Accredited laboratory methods used:	
pH	Potentiometric method (PB-01, edition 6 of 6.11.2009)
Specific electrical conductivity	Conductometric method (PB-02, edition 7 z 6.11.2009)
NH_4	Spectrophotometric method (PB-03, edition 5 of 6.11.2009)
Total alkalinity, HCO_3	Spectrophotometric method (PB-07, edition 4 of 6.11.2009)
Total organic carbon (TOC)	Spectrophotometric method (PB-09, edition 3 of 6.11.2009)
COD – chemical oxygen demand	Spectrophotometric method (PB-10, edition 3 of 6.11.2009)
colour	Spectrophotometric method (PB-11, edition 4 of 6.11.2009)
B, Ba, Ca, Cr, Fe, K, Mg, Mn, Na, P, SiO_2, Sr, Ti, Zn	ICP-AES method, according to PB-28 (edition 4 of 11.11.2009)
Hg	AAS method, according to PB-06 (edition 4 of 11.11.2009)
Li, Be, Al, V, Co, Ni, Cu, As, Se, Mo, Ag, Cd, Sn, Sb, Tl, Pb, U	ICP-MS method, according to PB-37 (edition 6 of 18.10.2010)
F, Br, Cl, NO_2, NO_3, HPO_4, SO_4	Ionic chromatography method, according to PB-04 (edition 12 of 16.01.2012)
Non-accredited laboratory methods used:	
Phenolic index, cyanides, AS (anionic surfactants)	Spectrophotometric method
Turbidity	Nephelometric method

The Laboratory of Gdańsk tested fracturing fluid (FF) and flowback fluid (FBF) samples for organic indicators: benzene, total BTEX, methane, C_2–C_{10} hydrocarbons, trichloroethene and tetrachloroethene. The determinations were made by gas chromatography.

2.7.3 Qualitative tests

Qualitative tests of organic components contained in fracturing and flowback fluids were made at the Central Chemical Laboratory of PGI-NRI.

The samples were extracted with dichloromethane solution and the extract was tested using gas chromatography with mass spectrometric detection (Agilent GC_MS 6890N-5973). The compounds were identified by comparing the produced mass spectra with spectra from the NIST Library holding spectra of over 200 thousand organic compounds.

The name of the identified compound, its full formula, CAS number, retention time, peak ratio and similarity of the recorded spectrum to the catalogue spectrum were stated in the test report. Any compounds detected in the dichloromethane extract that could not be exactly identified from the mass spectrum and Retention Index (RI) were reported as NN.

Test results with the "Probability" parameter equal to or higher than 75%, considering that probability level as a reliable identification of a compound, were included in the analysis of fracturing fluid composition. Statements showing the presence of compounds in the samples were made in order to identify those substances or their groups that may serve as contamination indicators. A relative content of a particular component in the sample was assessed considering its peak ratio.

2.7.4 Ecotoxicity tests

Samples of spent drilling mud, cuttings, fracturing and flowback fluids, as well as of flowback proppant and flowback wastes (i.e. flowback fluid stored in a ground pit, delivered to a treatment facility operated by an external service provider and located out of the test site, flowback fluid from Syczyno after treatment at that facility and solid waste from coarse separator at Lubocino site) were tested for ecotoxicity by Gdańsk University of Technology.

Ecotoxicology derives from toxicology, but there are differences between these two domains of science. Toxicology focuses on living organisms and the effects of xenobiotics thereon, mainly on uptake, propagation and metabolism of "poisons" in their systems. Ecotoxicology also deals with the fate of chemical substances but in the context of their distribution in the air, water, soil and sediments, as well on particular levels of the trophic chain. Moreover, ecotoxicology takes into account potential chemical and biological transformation of chemicals and focuses on contamination effects on the entire ecosystem, from the molecular and cellular level to the organisms. Biotests (experimental biological assay intended to demonstrate the presence of toxic substances in the environment or to establish the harmfulness thereof by estimating the effects on a living organism (compared to control trial)) is the key tool for the assessment of the biotoxicity.

The term "ecotoxicity testing" should be understood as an assessment of the effect of substances or their mixtures and physical parameters on living organisms – the effect can be **favourable** or **negative**. This statement is substantiated by observations made during this study: some of the samples have had a favourable effect on the biotest organisms – such phenomenon is called hormesis. Test organisms were growing better in contact with the sample that the control population.

A favourable or negative effect of agents on living organisms may appear shortly *(acute response)* or over a long time *(chronic response)* after the first contact of the test organism with the sample tested. Therefore, it is recommended to use different organisms in the tests (genetically modified bacteria that react to exposure after several minutes – acute response, and crustaceans or higher plants, wherewith validated procedures last several days – chronic response). Accordingly, a battery of biotests has been prepared (a set of biotests comprising organisms that represent different trophic levels). Moreover, since both solid and liquid samples were delivered for testing, it was proposed to use biotest organisms than live in open bodies of water and at the sediment-liquid interface. This would provide a more in-depth insight into the effect of the tested samples on the test organisms and, by the same, on the environment.

If a sample is found to have a negative effect on living organisms, ecotoxicological studies are expected to determine whether the involved substances are adsorbed or absorbed by the matrix of a solid sample. Absorbed substances are known to be easily extractable even with such mild extractants as water. Therefore, solid samples have been extracted or diluted and doped with a sediment of reference.

Samples tested under this project were diversified in terms of consistency: liquid and solid samples extracted with water, as well as dual phase samples.

Toxicity to the following species: bacterium *Vibrio fischeri* (water extracts and liquids), crustacean *Heterocypris incongruens* and mustard plant *Sinapis alba* (solid samples, water extracts and liquids) was tested in the delivered samples. These species were selected so as enable an assessment of toxicity to the widest range of organisms from various trophic levels (producers, consumers and destruents). Moreover, the presence of solid samples (process fluids with cuttings) should be considered when selecting the biotest battery: Ostracodtoxkit F^{TM} is the best known and the first biotest for direct contact of crustaceans with freshwater and brackish sediments/soils. The assay was performed using the tests specified in the Table 2.14 and according to standards stated therein.

Table 2.14. Ecotoxicity tests used

Microbiotest name	TAXON *Species*	Measured parameter Test time	Standard procedure
Microtox® (Strategic Diagnostics Inc., USA)	BACTERIA *Vibrio fischeri*	Bioluminescence inhibition 30 min	PN-EN ISO 11348-2(3):2002
Ostracodtoxkit F™ (MicroBioTests Inc., Nazareth, Belgium)	OSTRACODS *Heterocypris incongruens*	Growth inhibition; mortality 6 days	Acc. to manufacturer's recommendations (ISO 14371:2012 compliant)
Phytotoxkit F™ (MicroBioTests Inc., Nazareth, Belgium)	MUSTARD PLANT *Sinapis alba*	Sprouting and root growth inhibition 3 days	Acc. to manufacturer's recommendations (ISO 11269-1 compliant)

In the case of dual consistency samples, if preparing a homogenous mixture was impossible, toxicological tests were made separately for the two fractions: the supernatant (of a clarified and stabilized solution) and the precipitate.

Test procedures included the following steps:

- preparation of sediment water extracts for toxicity measurement;
- measurement of acute toxicity to bioluminescent *Vibrio fischeri* bacteria;
- assay based on the test of the crustacean *Heterocypris incongruens*;
- assay based on the test of *Sinapis alba* seeds.

Test procedure stage are described in detail below.

Preparation of water extracts of the sediments for toxicity measurement.

Water extracts of solid samples were prepared for toxicity measurement in accordance with the standard PN-EN ISO 11348-2(3):2002. Lyophilized sediment has been shaken in aerated demineralized water for 24 hours using a planetary shaker at 600 rev/min, then centrifuged and filtered using glass fiber mesh 0.45 µm filter. The filtrate (liquid collected under the funnel) was tested with bacteria-based Microtox®, and the solid fraction remaining on the filter using ostracoda-based Ostracodtoxkit F™ test and the plant-based Phytotoxkit F™ test. The procedure of sample preparation for testing is shown in detail in the following flowchart (Fig. 2.7).

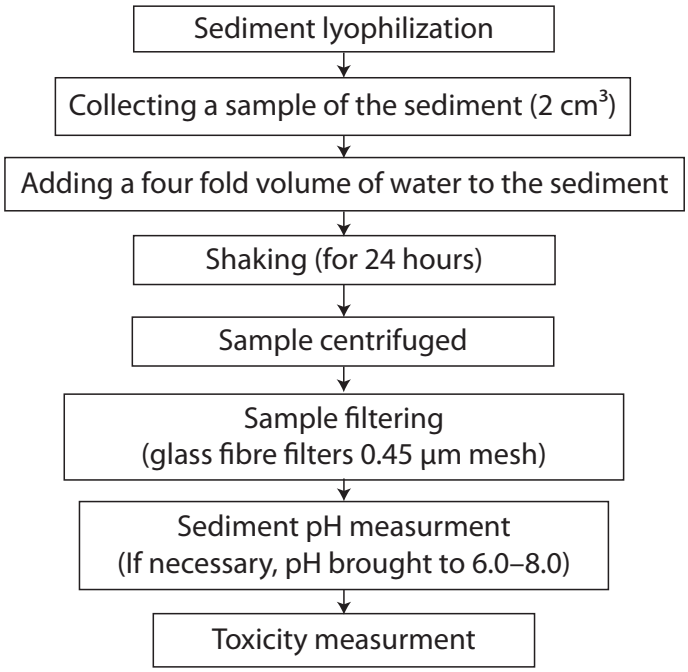


Fig. 2.7. Preparation of solid sample water extracts.

Acute toxicity measurement using bioluminescent *Vibrio fischeri* bacteria

Acute toxicity of liquid/water extract samples was determined using bioluminiscent *Vibrio fischeri* bacteria. Procedure called "81.9% Basic Test" was selected from 27 procedures offered by MicrotoxOmni™ software (of Strategic Diagnostics Inc., USA) intended for the analyzer Microtox® Model 500. This is a basic non-redundant test run as 1 blank sample + series of four 1:2 dilutions, starting with a concentration of 91%. The procedure of acute toxicity measurement according to PN-EN ISO 11348-2:2002 is shown on Fig. 2.8. The measurement system measures and calculates a correction factor (R_t) as the ratio of intensity of the light emitted by the blank sample in specific time of measurement to the intensity of light emitted prior to the beginning of the tests. Subsequently, the Gamma (G) parameter is calculated as the ratio of light quanta loss in time t to light intensity in time t for a given sample concentration, using the following formula:

$$G_t = \frac{R_t * I_0}{I_t} - 1$$

where:
G_t gamma parameter
R_t loss of light quanta in time t
I_0 light intensity in time t=0
I_t light intensity in time t for a given sample concentration

Percentage changes in a given parameter in time (EC_{20}, EC_{50}) are presented mathematically from the following formula:

$$\%\ effect\ in\ time\ t = \frac{G_t}{(1+G_t)} * 100$$

where: G_t – gamma parameter

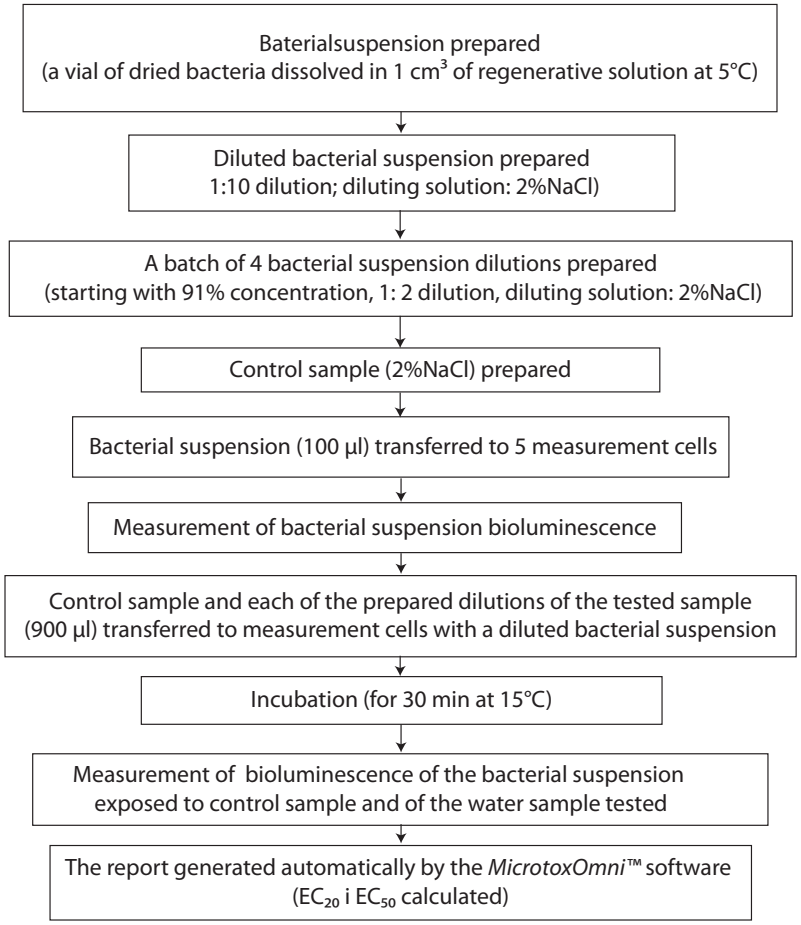


Fig. 2.8. Steps of toxicity measurement in liquid samples based on bioluminescent *Vibrio fischeri* bacteria.

Assay based on the test of the crustacean *Heterocypris incongruens*

Toxicity tests of solid and liquid samples included the determination of chronic toxicity based on a "direct contact" test – Ostracodtoxkit FTM(MicroBioTests Inc., Nazareth, Belgium). Toxicity assay is based on two effects: inhibition of growth in tested organisms and the determination of their lethality on contact with the sample. The procedure is shown on Fig. 2.9.

Specimens of *Heterocypris incongruens* hatched from cysts were selected for testing. Fifty two hours before the beginning of the test, the cysts were placed on Petri dishes with 10 cm3 of a standard medium prepared using salt ($NaHCO_3$, $CaSO_4$, $MgSO_4$, KCl) solutions supplied with the testing set. The cysts have been incubated at 25°C in permanent light of 3000–4000 lux. Freshly hatched specimens of *Heterocypris incongruens* were measured and transferred with glass micro-pipette to multi-well test plates filled with a solution of live algae and the sediment sample being tested. Subsequently, the plates have been incubated in darkness for 6 days at 25°C. After that time the length of live ostracodes was measured and compared with that established at the beginning of the test. Moreover, dead animals were counted in each well. Growth inhibition and mortality % was calculated by comparison with specimens living in the culture of reference.

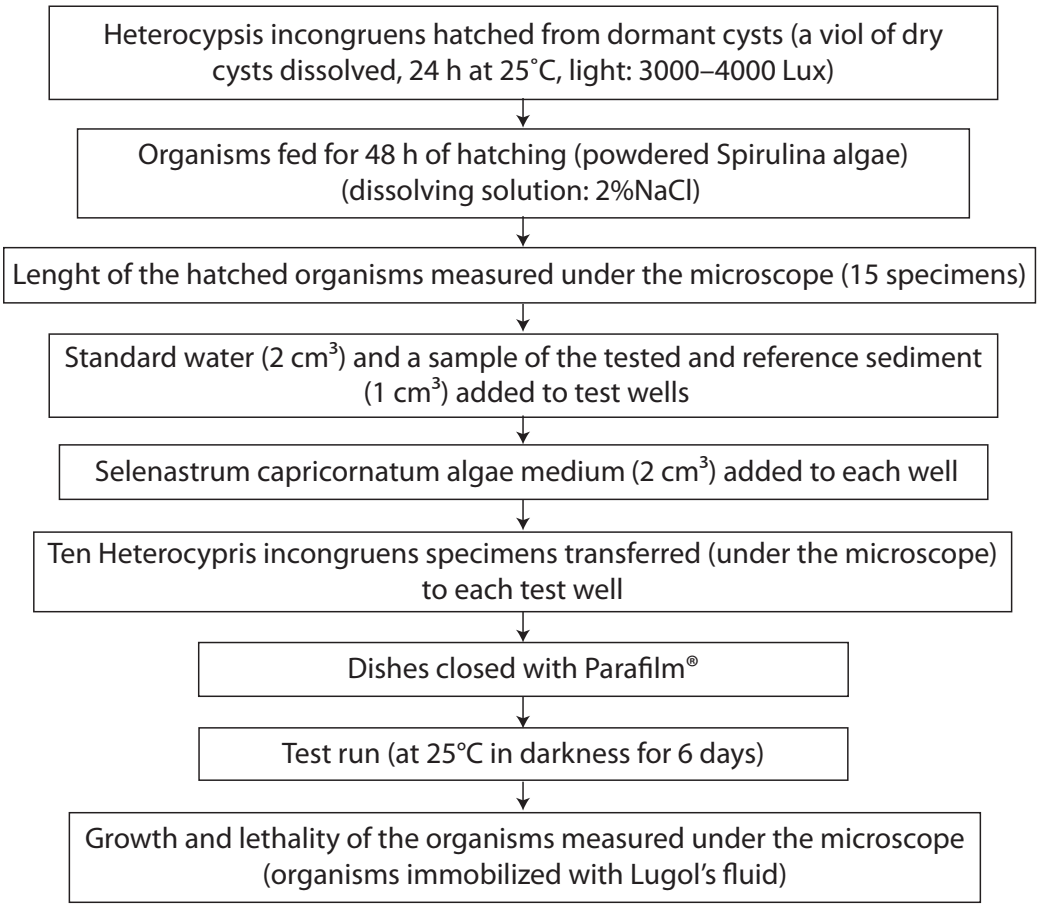


Fig. 2.9. Steps of toxicity measurement in liquid samples using a "direct contact" test – *Ostracodtoxkit F™*

Assay based on the test of *Sinapis alba* seeds

Toxicity assay is based on two effects: inhibition of seed sprouting and root growth rate as a result of contact with the sample. The procedure is shown schematically on Figure 2.10.

The procedures were modified accordingly to comply with test delivery requirements. The modifications were as follows:

- for the determination of solid sample toxicity (*Ostracodtoxkit F™ oraz Phytotoxkit F™)*, a batch of samples was prepared by adding a specific volume of the tested sediment to the wells and making up the sediment in the well with the sediment of reference to the final volume of 2 cm^3,

- for the determination of liquid sample toxicity (*Microtox®)* a batch of samples was prepared by adding to the wells (filled with an appropriate sediment of reference) specific volumes of the filtrate/supernatant tested (prepared according to the procedure shown on Fig. 2.11) and making up the liquid in the well with distilled water to the final volume of 2 cm^3.

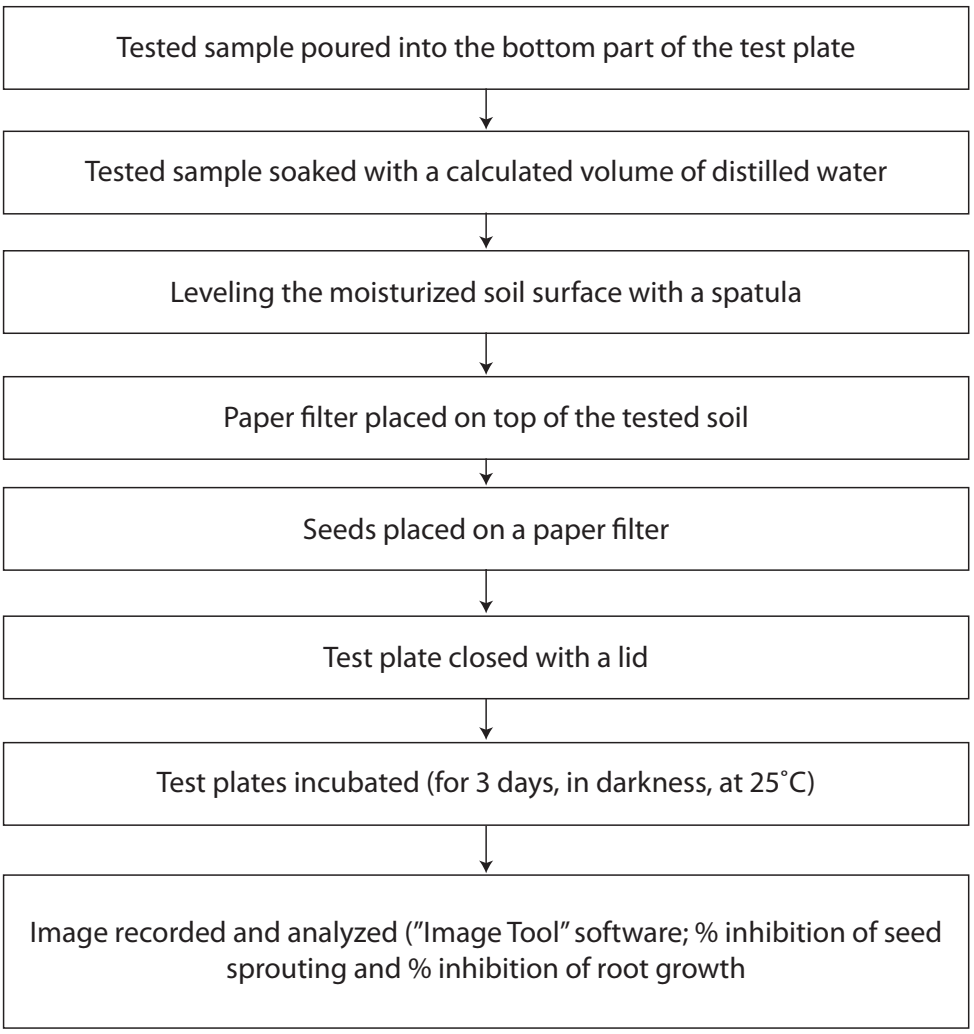


Fig. 2.10. Steps of acute toxicity measurement using *Sinapis alba* (applies to the sample of reference as well).

Filtrate samples of 0.9 cm^3 were collected for the *Microtox®* test, and of 2000 cm^3 and 5000 cm^3 for the *Ostracodtoxkit FTM* and *PhytotoxkitFTM* tests, respectively.

All ecotoxicity tests were made in three runs with arithmetic mean stated as the results. In the case of liquid sample toxicity tests, the sediment of reference was placed on the plate and distilled water was used as control.

3 Survey area

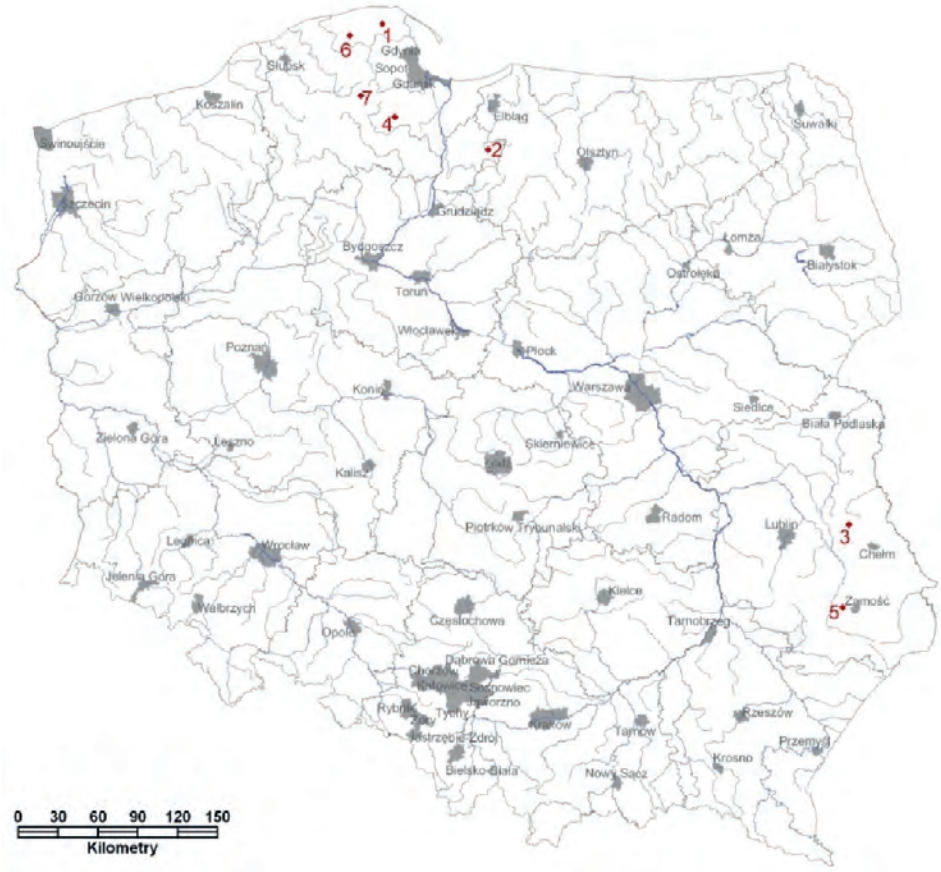
The survey area includes test sites that have been designated for the project around seven exploratory well locations. The term "test site" denotes a section of the space around a drilling well, in particular the drill site and its immediate neighbourhood. Test site boundaries are not marked, as they are delimited by theoretical range of potential environmental impacts from the drill site and may vary from one analysed environmental compartment to another.

Key test site selection criteria were:

- spatial representativeness, i.e. location of drilling wells within all unconventional oil and gas exploration areas in Poland,
- Operator's consent to join the project, deliver information and enable tests and monitoring at the drill site,
- delivery of drilling operations and hydraulic fracture stimulation throughout the term of the project.

Five tests sites (Syczyn and Zawada in the Lublin area and Lubocino, Stare Miasto and Wysin in the Pomeranian exploration area) have been initially selected to the project. Following a change in Operator's work program (fracture stimulation cancelled), the Gapowo test site was included in the project. In addition, the Łebień test site has been investigated as a follow-up of a research project delivered by Polish Geological Institute – National Research Institute (and other units) in 2011 for the Ministry of the Environment.

Test site locations are shown on the map (Fig. 3.1). Test site details are presented in Project Data Sheets (Appendix 1).



1 – Lubocino, 2 – Stare Miasto, 3 – Syczyn, 4 – Wysin, 5 – Zawada, 6 – Łebień, 7 – Gapowo

Fig. 3.1. Test site locations.

3.1 Spatial conditions

Test sites are located in the following meso-regions (according to Kondracki): Żarnowiec High Plain (Lubocino, Łebień), Kaszuby Lake District (Wysin, Gapowo), Iława Lake District (Stare Miasto), Łęczna–Włodawa Plain (Syczyn) and Zamość Depression (Zawada). The meso-regions are diversified in terms of relief an landscape.

As a general rule, the drill sites have been located in flat or almost flat areas to facilitate construction works. In the case of Lubocino, the drill site is located at a gentle slope of a small hill that has been levelled during construction works. That location proved to be problematic due to the runoff of surface and shallow ground water. An additional drainage system had to be built on the uphill side to address the problem. The Syczyn test site is located on a level ground, but in the proximity of a drainage ditch. Due to a small clearance between drill site and the bottom of the ditch, southwestern section of the fence has been damaged as backfill sand was washed away.

Administrative divisions are superimposed on the natural boundaries. Environmental assessments and studies on drill site impact on the environment should be based on environmental conditions and actual range of impacts, rather than administrative boundaries. All drill sites are located less than 3 km from adjacent communes. Syczyn test site is located in the Wierzbica commune, at a distance of approx. 950 m from the Cyców commune. Zawada test site is located in Zamość commune, about 1150 m away of the Szczebrzeszyn commune. Gapowo drill site is located in Stężyca commune, at a distance of approx. 550 m from the Sulęczyno commune.

Local and commune roads were most frequently used to access the sites. Unsurfaced access roads lead to Lubocino drill site (0.45 km), Stare Miasto (0.1 km, road paved with concrete slabs) Syczyn (0.15 km, road paved with concrete slabs) and to Zawada (1.5 km, macadam road).

Drill sites are usually located away of residential building, at a distance of 500 m or more (Table 3.1). Only at Syczyn and Gapowo residential areas are closer to the drill site. At Syczyn, the nearest isolated buildings are located in immediate proximity of the drill site, at a distance of approx. 50 m from the site boundary. Nevertheless, a top soil storage embankment situated between drill site and residential buildings effectively minimizes acoustic effects. Densely built-up village of Syczyn is located at a relatively short distance (approx. 200 m). At Gapowo test site, the nearest isolated farmstead is located about 360 m away of Gapowo drill site, at a busy provincial road 214, on the side opposite to the drill site.

All of the analysed drill sites are located in a farmland area or in its immediate neighbourhood.

Aggregate deposits (two pits in immediate proximity, of which one active) are located near Stare Miasto drill site. Proven but not produced deposits are located at Syczyn and near the Zwada test site (hard coal and kaolin, respectively). Proven and produced sand and gravel deposits are located 1.2 km away of Gapowo drill site.

The drill sites vary in terms of size and infrastructure facilities. The footprint ranged from 1.5 to 3.74 ha. Most of them are equipped with ground pits and all are surrounded by an embankment of the stored top soil.

Table 3.1. Drill site distance from the nearest residential buildings and commune's population density

Drill site	Distance from the nearest residential area		Commune's population density
	Isolated building	Densely built	
	[km]	[km]	[people/km^2]
1	2	3	4
Lubocino	0.12	0.8	49
Stare Miasto	0.65	0.65	22
Syczyn	0.05	0.2	37
Wysin	1.0	1.0	42

1	2	3	4
Zawada	1.0	1.5	113
Łebień	0.7	1.5	48
Gapowo	0.36	0.5	61
Stare Miasto	0.65	0.65	22

3.2 Selected regulatory and administrative aspects

The wells selected to the project have been drilled as part of geological works delivered under prospection and exploration concessions awarded to the Operators in accordance with applicable laws and regulations. Throughout the term of this project, the obligation to carry out the procedure of environmental impact assessment (EIA) depended on the then in effect legislative framework and applied to the entire concession area. In the case of a concession amendment request, the licensing authority, considering the scope of works and existing regulations, imposed the obligation o carry out the procedure of environmental impact assessment. Details of particular concessions and EIA procedures are stated below.

Lubocino Test Site

"Wejherowo" Concession No. 4/2009/p of 5 February 2009.

Decision by Wejherowo Commune Head of 25 September 2008, ref. RGPN/7666/59/2008 on environmental preconditions for granting the consent for project implementation;

Legal grounds:

Environmental Protection Law of 27 April 2001 (2006 Journal of Laws no. 129, Item 902, as amended); Council of Ministers' Ordinance of 9 November 2004 on the types of projects that may have a significant effect on the environment and on detailed conditions of imposing the obligation to prepare an environmental impact report on the project (Journal of Laws No. 257, Item 2573, as amended)

EIA procedure was motivated by potential significant impact on Natura 2000 sites located within the boundaries of the planned undertaking;

in accordance with Art. 155 of the Act of 3 October 2008 on providing information on the environment and environmental protection, public participation in environmental protection and environmental impact assessments (Journal of Laws No. 199, Item 1227), which took effect on 15 November 2008, the provisions that impose on an entity planning to develop the undertaking the obligation to obtain the decision on environmental preconditions do not apply to the entities that hold the decisions on environmental decisions awarded under provisions of Environmental Protection Law of 27 April 2001 (2006 Journal of Laws No. 129, Item 902, as amended)

Concession amendment: Environment Minister's Decision of 7 October 2010

Decision by Regional Director of Environmental Protection in Gdańsk of 5 August 2010, ref.: RDOŚ22-PN.I-6671-651(2)/10/AM on the absence of grounds for instituting the procedure;

(applies to the project of geophysical surveying)

Legal grounds:

The Act of 3 October 2008 on providing information on the environment and environmental protection, public participation in environmental protection and environmental impact assessments (Journal of Laws No. 199, Item 1227, as amended)

The EIA procedure was motivated by potential significant impact on Natura 2000 sites located within the boundaries of the planned undertaking that have been established after the concession awarding date

Concession amendment: Environment Minister's Decision of 21 May 2012

Decision by Regional Director of Environmental Protection in Gdańsk of 14 March 2012, ref.: RDOŚ-Gd-WOO.4210.53.15.2011.ER on environmental preconditions for awarding consent for project implementation;

(applies to the activities under concession amendment request)

Legal grounds:

The Act of 3 October 2008 on providing information on the environment and environmental protection, public participation in environmental protection and environmental impact assessments (Journal of Laws No. 199, Item 1227, as amended); Council of Minister' Ordinance of 9 November 2010 on undertakings that may have a significant effect on the environment (Journal of Laws No. 213, Item 1397)

Stare Miasto Test Site

"Elbląg" Concession No. 29/2008/p of 30 June 2008

Decision on environmental preconditions for the consent for project implementation not required;

Legal grounds:

Environmental Protection Law of 27 April 2001 (2006 Journal of Laws no. 129, Item 902, as amended); Council of Ministers' Ordinance of 9 November 2004 on the types of projects that may have a significant effect on the environment and on detailed conditions of imposing the obligation to prepare an environmental impact report on the project (Journal of Laws No. 257, Item 2573, as amended)

Concession amendment: Environment Minister's Decision of 27 July 2010

as above – concession amendment regarded concession transfer to another entity; the scope of works remained unchanged

Concession amendment: Environment Minister's Decision of 7 December 2010

Decision on environmental preconditions for the consent for project implementation not required; *it is prohibited to conduct seismic and drilling operations in the Jezioro Drużno PLB280013 and PLH280028 areas and to conduct seismic surveys with use of explosives; should it occur that such operations are required, the concession must be amended and the decision on environmental precondition obtained*

Legal grounds:

Environmental Protection Law of 27 April 2001 (2006 Journal of Laws no. 129, Item 902, as amended); Council of Ministers' Ordinance of 9 November 2004 on the types of projects that may have a significant effect on the environment and on detailed conditions of imposing the obligation to prepare an environmental impact report on the project (Journal of Laws No. 257, Item 2573, as amended) *in accordance with Council of Minister' Ordinance of 9 November 2010 on undertakings that may have a significant effect on the environment (Journal of Laws No. 213, Item 1397), existing provisions shall apply to all procedures instituted prior to its effective day*

Syczyn Test Site

"Wierzbica" Concession No. 28/2007/p of 30 October 2007

Decision on environmental preconditions for the consent for project implementation not required;

Legal grounds:

Environmental Protection Law of 27 April 2001 (2006 Journal of Laws no. 129, Item 902, as amended); Council of Ministers' Ordinance of 9 November 2004 on the types of projects that may have a significant effect on the environment and on detailed conditions of imposing the obligation to prepare an environmental impact report on the project (Journal of Laws No. 257, Item 2573, as amended)

Concession amendment: Environment Minister's Decision of 28 April 2010

as above – concession amendment regarded concession transfer to another entity; the scope of works remained unchanged

Concession amendment: Environment Minister's Decision of 30 October 2012

Decision on environmental preconditions for the consent for project implementation not required; *it is prohibited to conduct seismic and drilling operations within Natura 2000 sites and to conduct seismic surveys with use of explosives;*

Legal grounds:

The Act of 3 October 2008 on providing information on the environment and environmental protection, public participation in environmental protection and environmental impact assessments (Journal of Laws No. 199, Item 1227, as amended); Council of Minister' Ordinance of 9 No-

vember 2010 on undertakings that may have a significant effect on the environment (Journal of Laws No. 213, Item 1397)

Concession amendment: Environment Minister's Decision of 1 February 2013

Decision by Wierzbica Commune Head of 17 October 2012, ref. Bd.3.6220.5.2011 on environmental preconditions for granting consent for project implementation;

Legal grounds:

The Act of 3 October 2008 on providing information on the environment and environmental protection, public participation in environmental protection and environmental impact assessments (Journal of Laws No. 199, Item 1227, as amended); Council of Minister' Ordinance of 9 November 2010 on undertakings that may have a significant effect on the environment (Journal of Laws No. 213, Item 1397)

Wysin Test Site

"Stara Kiszewa" Concession No. 1/2011/p of 11 January 2011

Decision by Regional Director of Environmental Protection in Gdańsk of 10 September 2012, ref.: RDOŚ-22-WOO.6670/26-12/08/09/10ER on environmental preconditions for awarding consent for project implementation;

Legal grounds:

The Act of 3 October 2008 on providing information on the environment and environmental protection, public participation in environmental protection and environmental impact assessments (Journal of Laws No. 199, Item 1227, as amended); Council of Ministers' Ordinance of 9 November 2004 on the types of projects that may have a significant effect on the environment and on detailed conditions of imposing the obligation to prepare an environmental impact report on the project (Journal of Laws No. 257, Item 2573, as amended)

Zawada Test Site

"Zwierzyniec" Concession No. 70/2009/p of 10 December 2009

Decision on environmental preconditions for the consent for project implementation not required; *it is prohibited to conduct seismic and drilling operations within Natura 2000 sites*

Legal grounds:

The Act of 3 October 2008 on providing information on the environment and environmental protection, public participation in environmental protection and environmental impact assessments (Journal of Laws No. 199, Item 1227, as amended); Council of Ministers' Ordinance of 9 November 2004 on the types of projects that may have a significant effect on the environment and on detailed conditions of imposing the obligation to prepare an environmental impact report on the project (Journal of Laws No. 257, Item 2573, as amended)

Concession amendment: Environment Minister's Decision of 30 September 2011

Decision by Regional Director of Environmental Protection in Rzeszow of 15 July 2011, ref.: WPN.430.123.2011.BA-2 PS on waiving the obligation to prepare an environmental impact assessment *(applies to Vibroseis-based seismic surveying)*

Decision by Regional Director of Environmental Protection in Lublin of 16 August 2011, ref.: WST. III.430.6.2011.PS on waiving the obligation to prepare an environmental impact assessment *(applies to Vibroseis-based seismic surveying)*

Legal grounds:

The Act of 3 October 2008 on providing information on the environment and environmental protection, public participation in environmental protection and environmental impact assessments (Journal of Laws No. 199, Item 1227, as amended)

Łebień Test Site

"Lębork" Concession No. 16/2007p of 23 October 2007

Decision on environmental preconditions for the consent for project implementation not required; *oit is prohibited to conduct seismic and drilling operations within Natura 2000 sites*

Legal grounds:

Environmental Protection Law of 27 April 2001 (2006 Journal of Laws No. 129, Item 902, as amended); Council of Ministers' Ordinance of 9 November 2004 on the types of projects that may have a significant effect on the environment and on detailed conditions of imposing the obligation to prepare an environmental impact report on the project (Journal of Laws No. 257, Item 2573, as amended)

Concession amendment: Environment Minister's Decision of 12 December 2008

Decision on environmental preconditions for the consent for project implementation not required; *it is prohibited to conduct seismic and drilling operations within Natura 2000 sites*

Legal grounds:

Environmental Protection Law of 27 April 2001 (2006 Journal of Laws No. 129, Item 902, as amended); Council of Ministers' Ordinance of 9 November 2004 on the types of projects that may have a significant effect on the environment and on detailed conditions of imposing the obligation to prepare an environmental impact report on the project (Journal of Laws No. 257, Item 2573, as amended)
in accordance with Art. 155 of the Act of 3 October 2008 on providing information on the environment and environmental protection, public participation in environmental protection and environmental impact assessments (Journal of Laws No. 199, Item 1227), which took effect on 15 November 2008, the provisions of Environmental Protection Law of 17 April 2001 (2006 Journal of Laws No. 129, Item 902, as amended) shall apply to administrative proceedings instituted prior to the effective day of the Act

Concession amendment: Environment Minister's Decision of 26 October 2010

Decision on environmental preconditions for the consent for project implementation not required; *it is prohibited to conduct seismic and drilling operations within Natura 2000 sites and to conduct seismic surveys with use of explosives*

Legal grounds:

Environmental Protection Law of 27 April 2001 (2006 Journal of Laws No. 129, Item 902, as amended); Council of Ministers' Ordinance of 9 November 2004 on the types of projects that may have a significant effect on the environment and on detailed conditions of imposing the obligation to prepare an environmental impact report on the project (Journal of Laws No. 257, Item 2573, as amended).

Concession amendment: Environment Minister's Decision of 18 October 2013

Decision on environmental preconditions for the consent for project implementation not required; *to the extent specified in the request, i.e. seismic operations conducted without use of explosives and out of Natura 2000 sites*

Legal grounds:

The Act of 3 October 2008 on providing information on the environment and environmental protection, public participation in environmental protection and environmental impact assessments (Journal of Laws No. 199, Item 1227, as amended); Council of Minister' Ordinance of 9 November 2010 on undertakings that may have a significant effect on the environment (Journal of Laws No. 213, Item 1397, as amended)
concession amendment request made before effective date of Ministers' Council's Ordinance of 25 June 2013 on the amendment of the Ordinance on undertakings that may have a significant effect on the environment (2013 Journal of Laws, Item 817) – the existing provisions have been applied in accordance with Paragraph 2 of the Ordinance

Concession amendment: Environment Minister's Decision of 18 September 2014

Decision on environmental preconditions for the consent for project implementation not required; *it is prohibited to conduct seismic and drilling operations within Natura 2000 sites, drill wells deeper than 1000 m in buffer zones of water intakes, freshwater reservoirs and in environmentally protected areas*

Legal grounds:

The Act of 3 October 2008 on providing information on the environment and environmental protection, public participation in environmental protection and environmental impact assessments (Journal of Laws No. 199, Item 1227, as amended); Council of Minister' Ordinance of 9 November 2010 on undertakings that may have a significant effect on the environment (Journal of Laws No. 213, Item 1397, as amended)

Gapowo Test Site

"Bytów" Concession No. 17/2010/p of 17 March 2010

Decision on environmental preconditions for the consent for project implementation not required; *it is prohibited to conduct seismic and drilling operations within Natura 2000 sites*

Legal grounds:

The Act of 3 October 2008 on providing information on the environment and environmental protection, public participation in environmental protection and environmental impact assessments (Journal of Laws No. 199, Item 1227, as amended); Council of Ministers' Ordinance of 9 November 2004 on the types of projects that may have a significant effect on the environment and on detailed conditions of imposing the obligation to prepare an environmental impact report on the project (Journal of Laws No. 257, Item 2573, as amended).

Concession amendment: Environment Minister's Decision of 1 June 2011

Decision on environmental preconditions for the consent for project implementation not required; *it is prohibited to conduct seismic and drilling operations within Natura 2000 sites*

Legal grounds:

The Act of 3 October 2008 on providing information on the environment and environmental protection, public participation in environmental protection and environmental impact assessments (Journal of Laws No. 199, Item 1227, as amended); Council of Minister' Ordinance of 9 November 2010 on undertakings that may have a significant effect on the environment (Journal of Laws No. 213, Item 1397)

Concession amendment: Environment Minister's Decision of 3 July 2012

Decision by Stężyca Commune Head of 14 June 2012 r. on environmental preconditions for granting the consent for project implementation;

Legal grounds:

The Act of 3 October 2008 on providing information on the environment and environmental protection, public participation in environmental protection and environmental impact assessments (Journal of Laws No. 199, Item 1227, as amended); Council of Minister' Ordinance of 9 November 2010 on undertakings that may have a significant effect on the environment (Journal of Laws No. 213, Item 1397)

Concession amendment: Environment Minister's Decision of 14 November 2013

Decision by Regional Director of Environmental Protection in Gdańsk of 6 March 2013, ref.: RDOŚ-Gd-WOO.4210.22.2012.ER.16 on environmental preconditions for project implementation;

Legal grounds:

The Act of 3 October 2008 on providing information on the environment and environmental protection, public participation in environmental protection and environmental impact assessments (Journal of Laws No. 199, Item 1227, as amended); Council of Minister' Ordinance of 9 November 2010 on undertakings that may have a significant effect on the environment (Journal of Laws No. 213, Item 1397)

the entrepreneur has obtained for the undertaking specified in the request a binding decision on environmental preconditions before the effective date of Ministers' Council's Ordinance of 25 June 2013 on the amendment of the Ordinance on undertakings that may have a significant effect on the environment (2013 Journal of Laws, Item 817); in accordance with Paragraph 2 of the aforementioned Ordinance, the existing provisions shall apply; the decision on environmental preconditions was required on the day the request was made

3.3 Diversity of geological conditions and the quality of natural sealing

There are two potential risks associated with the effect of fracturing fluids on the tectonic structures in the area of shale gas accumulations: (i) upward migration of fracturing fluid and/or methane via fractures and faults, and (ii) seismic events at a fault reactivated by fracture stimulation.

3.3.1 Pomeranian region – structural context of hydraulic fracture stimulation risks

Sealing complexes

There are two major sealing complexes in the Pomeranian region: Silurian and Zechstein formations.

The Silurian sealing complex extends from the top of the topmost hydraulically fractured strata (Llandovery) to the Permian bottom where several metre-thick permeable sandstones occur only locally. Due to a widespread distribution of geotectonic factors that shaped sedimentation and erosion of the Silurian sealing complex, its thickness changes smoothly in the area of investigations (Fig. 3.2) from 3000 m in the west to minimum 300 m in the east. In the easternmost Stare Miasto-1 well, a minimum thickness of the Silurian sealing complex is in excess of 700 m. Since faults reported from Pomerania have throws reaching up to 100 m, they are unable to compromise the continuity of the sealing complex. In that case, the screen might be partially compromised exclusively along the fractured zones that surround the faulted zones. Such faults should display recent tectonic activity, as inactive fractures are usually mineralised with calcium carbonate. As no recent activity of tectonic zones has been reported from Pomerania, also that scenario should be considered as little probable.

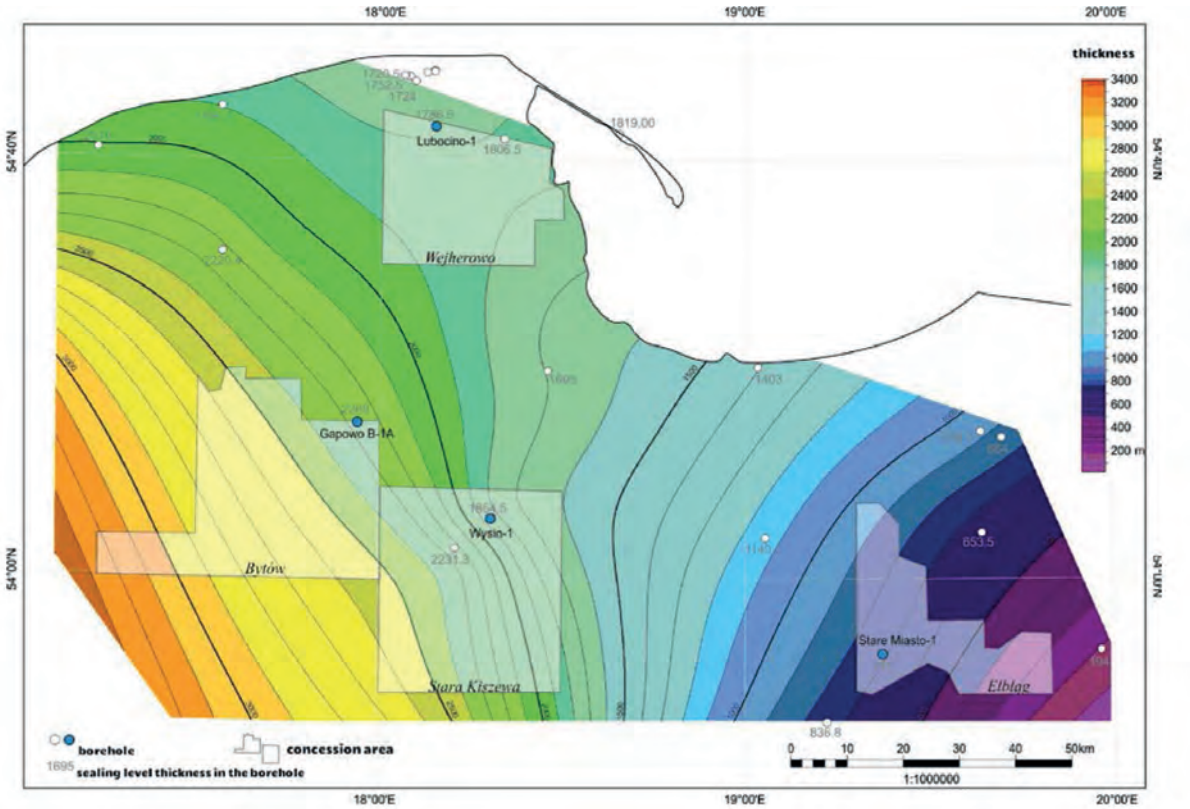


Fig. 3.2. Thickness of the Silurian sealing complex from Llandovery top to the Permian bottom.

The Zechstein sealing complex is composed of the sediments of the three oldest cyclotems, of which the most important are the salts of lower cyclotems: the Oldest Halite (Na1) and the Older Halite (Na2) that occur throughout the region and form the main sealing beds (Wagner, 1988). Besides these complexes, the sediments of younger cyclotems (PZ2 and PZ3), mainly sulphates and carbonates, are of a relatively smaller thickness. From among the Zechstein evaporites, only dolomites do not display sealing properties. Although salt samples have not been tested for permeability, it is reasonable to conclude that salts have the best sealing properties with permeabilities in the order of several nano Darcy at the most (Kettel, 1997). Due to a homogenous structure, minimal porosity and small viscosity, brittle destructions – including hydraulically induced fractures – do not develop in salt rocks at realistically assumed tectonic deformation rates in Pomerania. In the case of analysed technological processes, the halite and anhydrite screen should be considered as an excellent isolation for fracture propagation and migration of fracturing fluids and of natural gas.

Throughout the analysed area, thickness of the Zechstein sealing complex passes gently from 280 m in the north to approx. 500 m in the south (Fig. 3.3). Seismic profiles from the surveyed area revealed only a few faults penetrating into the Zechstein bottom, but none of them passes through the entire complex of Zechstein evaporites. They do not pose any risk to the tightness of the Zechstein complex.

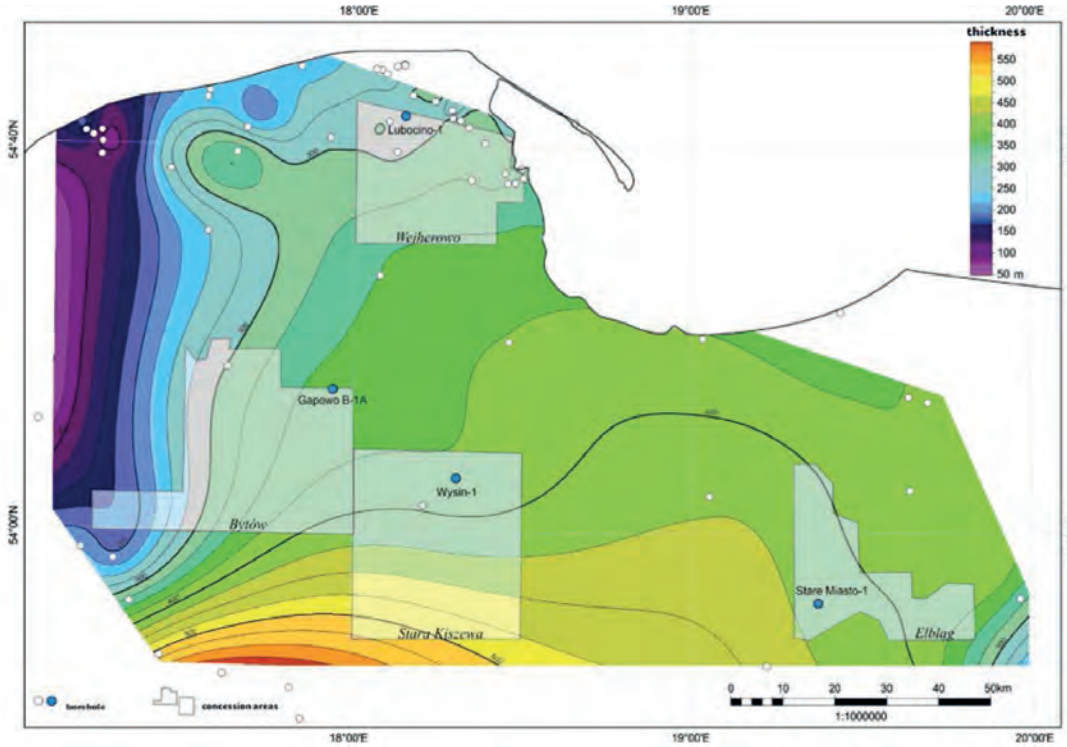


Fig. 3.3. Zechstein sealing complex thickness.

The properties of the sealing complexes have been analysed for three test sites – Lubocino, Stare Miasto and Wysin. Due to an insufficient amount of data from the Stare Miasto-1 well and missing sampling depth descriptions from Lubocino-1 well, Wysin-1 and Kościerzyna IG-1 wells were adopted as benchmarks. In the Wysin-1 well, average effective porosities (according to interpreted geophysical well logging data) amount to 1.51% in Zechstein rocks, but the average is inflated by Main Dolomite formations with porosities up to 10%, while other formations of the complex have near 0% porosities. Average porosity of the Ludlow and Pridol formations is equal to 1.40%. At Kościerzyna IG-1, average effective porosities (as determined by core sample testing) were found to be equal to 1.73% in Zechstein formations and to 1.07 in Ludlow and Pridol formations.

The Wejherowo Concession Operator provided permeability data for shale complexes, as established on the basis of core samples from Lubocino-1 well. Samples tested for permeability were described collectively as "Ordovician/Silurian samples" (depth not indicated). Considering the coring program for that well, it is certain that the samples have been collected from the interval of 2228–2907 m (Ordovivian and Lower Silurian). The average of 96 tests made in that interval is 2.084 mD, but the median is equal to 0.071 mD. Almost all of the determinations reflect fracture-related permeability, potentially inflated by core relaxation and sample preparation procedures. Therefore, it is concluded that Ordovician and Silurian formations have excellent in situ sealing properties.

In the Zechstein complex, only three Main Dolomite samples have been tested for permeability at Niestępowo-1 well (the analysis of regional trends is based on available preexisting data of adequate quality). The results that range from 169 mD to 1 mD demonstrate a huge variability of Dolomite permeabilities, a typical feature of that cavernous collector rock. Main Dolomite is the only formation in the Zechstein complex that does not provide a good sealing. However, its minor thickness (several metres) make it unimportant for the sealing properties of the whole evaporate complex. Salt and anhydrite beds, as established on the basis of downhole logs, should be considered as excellent sealing formations.

Near-well fault zones

A hypothetical presence of a conductive faulted zone is closely correlated with the complexes that are dissected by the fault. In all Pomeranian test sites tested, the hydraulically fractured Ordovician and lowermost Silurian (Llandovery) formations are overlain by thick impervious younger Silurian shales that, in addition, are covered by Zechstein evaporites. It should be reminded again at this point that the evaporites, halite and anhydrite in particular, are the most effective natural sealing rocks that commonly occur on Earth. The thicknesses of the sealing complexes are several times higher than the throws of faults located in these complexes. This precludes the possibility of compromising the continuity of the aforementioned sealing. Faults disrupting the continuity of Zechstein formations were not reported from Pomerania and maximal throws of the faults that are accommodated in the Silurian only occasionally exceed 100 m and are never in excess of 200 m. Accordingly, the sealing of shale complexes in Pomerania and the tightness of the fault zones that dissect them, is unquestionable. The presence of fault zones within the shale formations may only hinder fracture stimulation operations, but this problem can be addressed at drilling location planning stage and by deviation of the horizontal wellbore segment.

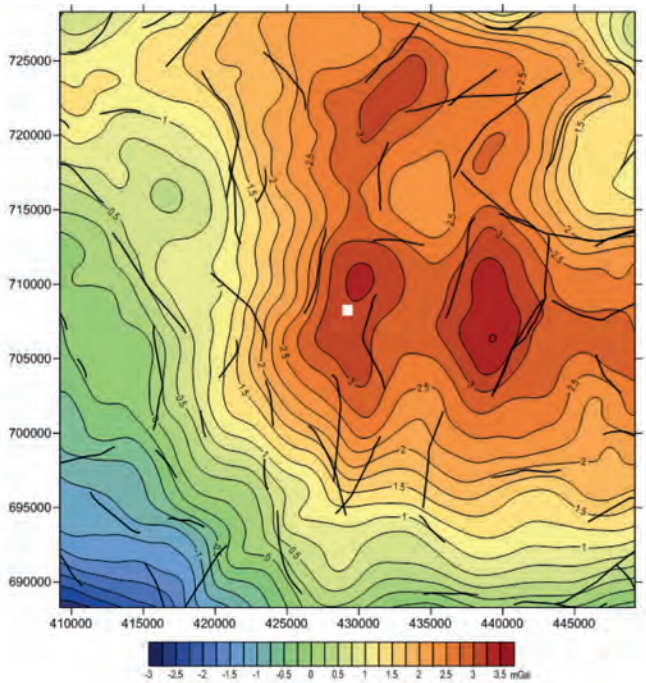
An analysis of the tectonics of particular test sites is summarized below. Considering a limited set of data provided by the Operators the analysis is not based on full industrial information collected on the sites. Available information sourced at National Geological Archives complemented the concession data.

Gapowo Test Site

The set of geological data from the neighbourhood of the Gapowo-1 well did not allow for an interpretation of the tectonic structure in that area, mainly due to a poor quality of seismic profiles in the proximity of the well. It was only possible to establish on their basis that the sealing complex of Zechstein evaporities is continuous throughout the area and the bottom of that complex has not been tectonically deformed. No faults were found beneath the Zechstein complex, but this may be due to a low quality of signal acquisition.

An analysis of gravimetric lineaments indicates that NNE-SSW discontinuities may occur below the Zechstein at a distance of 2 and 3 km from the Gapowo B-1 well, striking east and westward, respectively (Fig. 3.4). However, the lineaments are not continuous enough to suggest the presence of major fault zones and may arise from density contrasts other than fault displacement, for example due to the diversity of the Zechstein facies. Moreover, an interpretation based on resistivity logs of the horizontal borehole segment does not reveal a concordance of fault strike with the azimuth of gravimetric lineaments. Downhole logs identified small NW-SE faults. Furthermore, it has been established that the predominant NW-SE steep joints (NW-SE) trending is more or less perpendicular to the horizontal borehole axis, but in that case vertical drilling-induced fractures cannot be ruled out.

All available data indicate that there are no fault zones of a magnitude that may compromise sealing integrity on the area of Gapowo B-1 well. Therefore, it is concluded that there are no risks of upward fracturing fluid or gas migration to the ground surface and commercial acquifers.

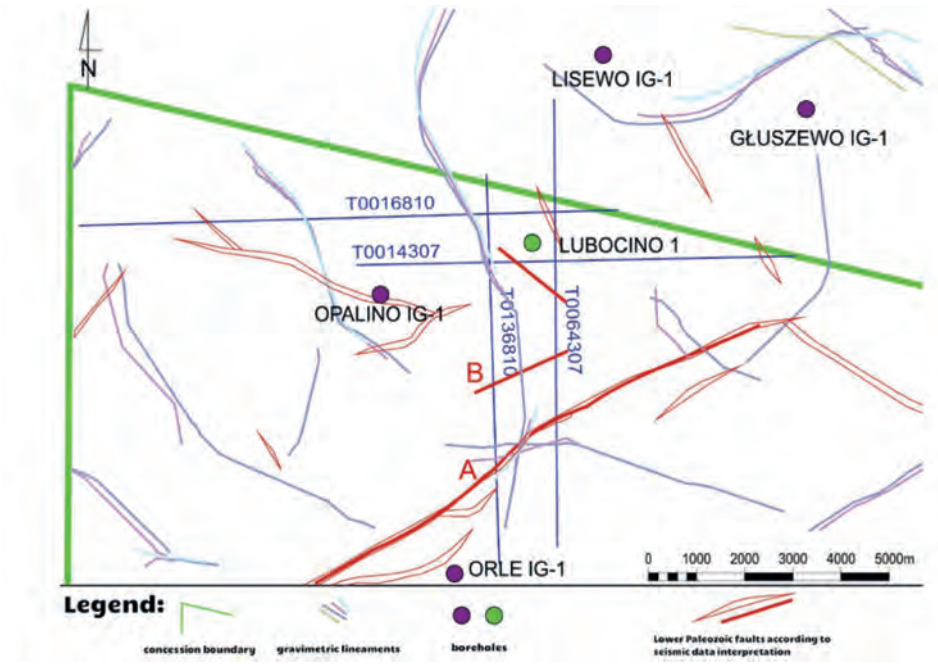


The white square denotes the location of the Gapowo B-1 well gravimetric lineaments are marked with black lines.

Fig. 3.4. Map of Bouguer reduced anomalies showing the difference between levels of upward analytical extension to the levels of 1 km and 5 km.

Lubocino Test Site

Tectonics interpretation is based on preexisting archive data. None of the faults located in the proximity of the well (Fig. 3.5) dissects the Zechstein complex of which bottom (and the overlying Mesozoic complex) is horizontal. Whatever the Zechstein bottom structures might be, the undisturbed evaporite complex is an impermeable barrier to the migration of fracturing fluids, gas and crude oil. Small faults located several hundred metres NE and SE of the Lubocino-1 (and Lubocino-2H) may only have an effect on drilling and effectiveness of fracture stimulation of the prospective shale horizon.



thin red lines – faults according to seismic documentation (Grzywa, Trzupek, 2011)
thick red lines – according to additional interpretation made under the Project

Fig. 3.5. Interpretation of main faults, lower Paleozoic level.

During hydraulic fracture stimulation of the horizontal borehole segment (Lubocino 2-H), the Operator hired an external service company to deliver micro-seismic monitoring for the determination of the hydraulic fracture propagation range (Fig. 3.6). It was established that hydraulic fractures were induced in the interval extending from the bottom of Caradocian to the Wenlock bottom and their height (total vertical length) is not in excess of 80 m. Downward propagation of fractures is limited by the impenetrable barrier of the Kopalino formation limestones, but the upper barrier, composed of beds with a higher content of clay minerals, is mechanically less effective. The horizontal range of the induced fractures was more extensive – on average, they reached a distance of maximum 180 m from the horizontal borehole segment.

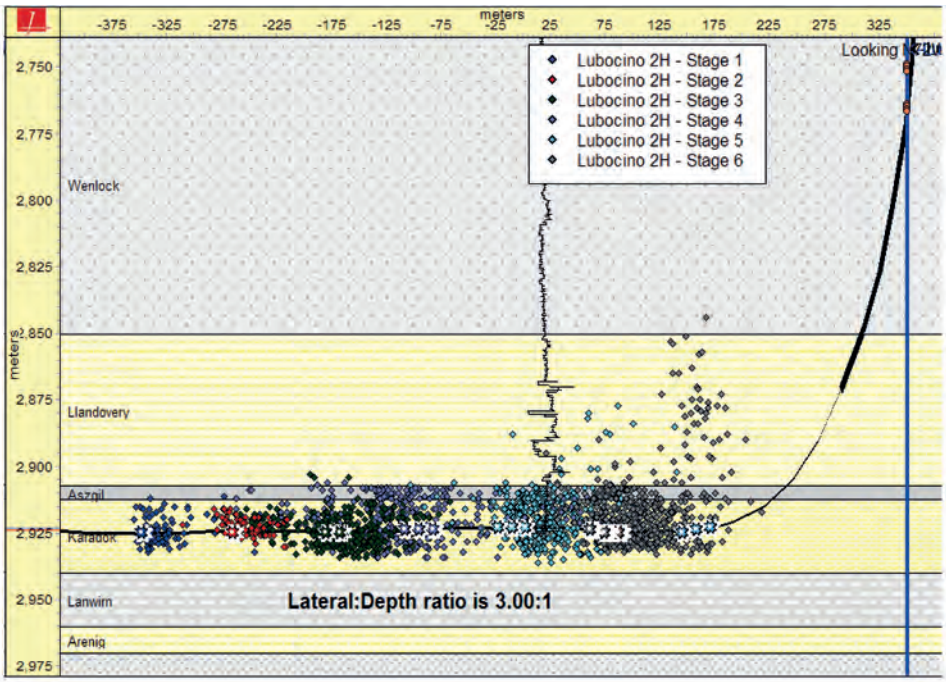
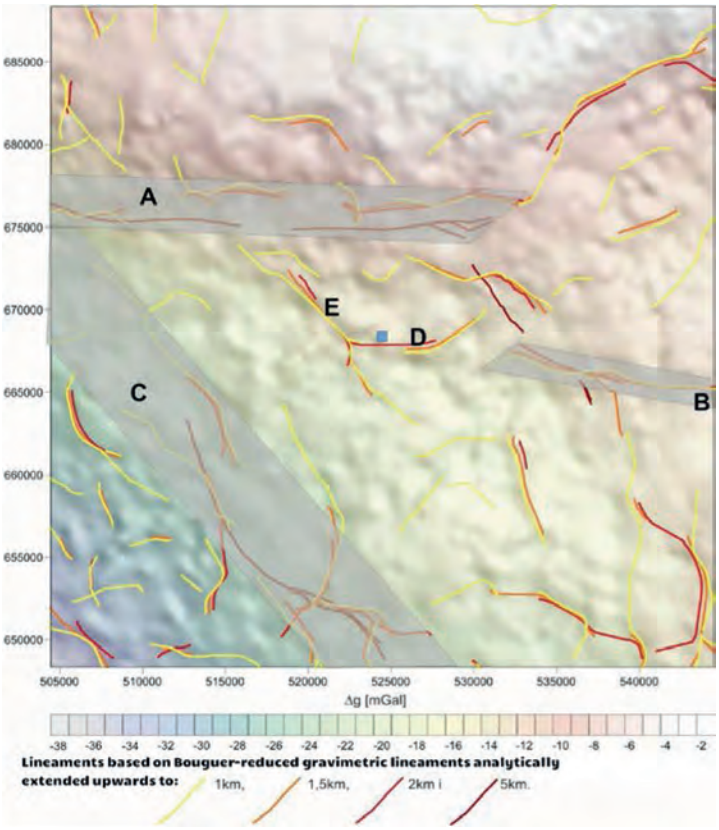


Fig. 3.6. Location of micro-seismic centres at fracturing stimulation of Lubocino-2H well, vertical cross-section, Upper Ordovician and Lower Silurian profile.

Stare Miasto Test Site

Low quality seismic profiles from the Elbląg Concession permitted only to establish the continuity of the reflexes from Zechstein top and bottom. Only in immediate proximity of the Stare Miasto-1K well a discontinuity of the reflexes may indicate the presence of a fault that dissects the Zechstein top and bottom. Since the throw of that hypothetical fault is not in excess of several tens of metres, it does not pose a risk of compromising the continuity of the evaporite complex.

A gravimetric lineament-based interpretation of the faults revealed a potential presence of three larger fault zones located further away (over 5 km) of the well (Fig. 3.7). Moreover, a small longitudinal fault, suggested by both seismic profile and gravimetric analysis, may exist in Permian formations in immediate proximity (< 1 km) of the well. That hypothetical fault may have an effect on fracturing operations, but there are no grounds to suspect a potential risk to the integrity of the complex from the top.



Blue square denotes the location of the Stare Miasto-1 well

Fig. 3.7. Gravimentric lineaments for the levels of 1, 1.5, 2 and 5 km shown against the background of Bouguer reduced anomalies with elements of tectonic interpretation (grey fields).

The range of the fractured space around the horizontal borehole segment has been broadly defined using poor quality micro-seismic monitoring data. Asymmetry of micro-seismic event hypocentres indicates potential contribution of existing structures to fracture propagation. Although the fractures are more extensive vertically than horizontally, no seismic events have been recorded more than 100 m from the well. Considering potential error in establishing the location of seismic events it is reasonable to conclude that the induced fractures did not go beyond a zone of 200 m from the well (both vertically and horizontally), which means a comfortable margin of safety in terms of potential penetration of fracturing fluids, even across the nearest Silurian sealing complex.

Wysin Test Site

According to the interpretation of 2D seismic data (Fig. 3.8), the Wysin-1 well is located in between two NW-SE faults that run about 4 km away on both sides of the well. The distance from the well precludes any direct impact on the effects of fracturing operations. Tectonic discontinuities seen on the profiles are petering out in Lower Silurian and seismic signal distortions reach the Zechstein bottom. No reflex disruptions within Zechstein formations are seen on any of the analyzed lines above the faulted zones. The sealing Zechstein evaporites are invariably an impermeable barrier to upward migration of fluids from the lower Paleozoic complex. In that case, it is less important that Silurian formations that overlie the potentially fracture stimulated Llandovery complex are characterized by extremely low permeability to liquids and any potential fault zones developed therein have probably sealing properties due to a higher content of clay minerals. Well location on a step in between the faults may only be of relevance in terms of predominant secondary joints that should determine the preferred direction of the horizontal borehole segment.

Due to a sparse network of seismic lines, the location of faults correlated within seismic profiles should be considered as hypothetical only. Gravimetric lineaments do not match the faults established from seismic data (Fig. 3.8). However, regardless of the assumed location of faults in the proximity of the analysed well the fault zones do not create pathways for upward migration of fluids to the ground surface and commercial aquifers.

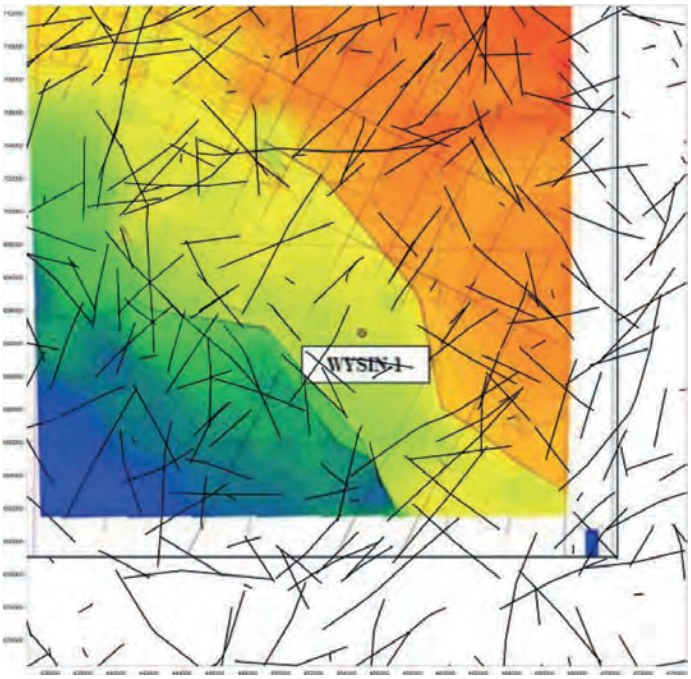


Fig. 3.8. Gravimetric lineaments based on Bouguer anomalies and fault locations established by seismic surveys.

3.3.2 Lublin region – structural context of hydraulic fracture stimulation risks

Sealing complexes

Comparing with Pomerania, facies distribution and extant thicknesses of sealing complexes are much more diversified in the Lublin region. Since the Lublin Basin is divided by major fault zones, the sealing complexes are not continuous throughout the surveyed area and should be considered independently in each of the locations.

The Upper Silurian (Ludlow and Pridoli) formations, located above the potentially fracture stimulated Lower Silurian beds, should be considered as the main sealing complex. At Syczyn OU-2K well, this complex is 857 m thick. Considering that prospective interval is located at a depth of approx. 2700 m, this should ensure its upward sealing. The sealing should be even better at Zwierzyniec-1 well, where the Upper Silurian complex was found to be 1387 m thick and the prospective interval is located at a depth greater than 3100 m.

Local lower Paleozoic sealing complexes are located above the main Silurian complex: the Devonian Zwoleń and Sycyn Formations and the Carboniferous Lublin and Huczwa Formations. Their sealing properties are less favourable comparing with lower Paleozoic formations. More importantly, their lateral facies variability is much higher so that their patterns and ranges have to be analysed separately for each location. For example, should the Silurian sealing be thinner in the Syczyn OU-2K well (than in the Zwierzyniec-1 well), there would be still an additional, in total 840 m thick, Devonian and Carboniferous sealing.

As there is no evaporite cover in the analysed areas of the Lublin Basin, any complexes younger than Carboniferous can not be considered as effective sealing. In spite of only slight tectonic deformations in this region, serial fractures that adversely affect the sealing properties should be expected to occur due to a high share of brittle carbonate rocks.

In the Lublin Region, an analysis of the sealing complexes was carried out for the Syczyn and Zawada test sites. As only scarce data were available from recently drilled wells (Syczyn OU-2K and Zwierzyniec-1, respectively), pre-existing data from Busówno IG-1, Wierzbica 1, Izbica IG-1, Sułowiec IG-1 and Ruskie Piaski IG-2 wells were used to prepare a reliable assessment of sealing in the two test sites. However, pre-existing wells of reference to the Zawada test site have not penetrated into Upper Silurian formations that are considered as the main sealing for the Zwierzyniec 1 well. Therefore, it has to be assumed that sealing properties of Upper Silurian formations are relatively constant in the tested area. In core samples from Busówno IG-1 well, average effective porosity of that 787 m thick interval was 2.01% (7 samples tested) and horizontal permeabilities were found to be less than 0.75 mD in each of the 9 samples tested. The actual permeability of these samples is likely to be lower, as test resolution was insufficient for a more precise determination. Also downhole logs have suggested good sealing properties of that complex.

Four additional sealing complexes were identified in the Syczyn test site: the Devonian Zwoleń and Sycyn Formations and the Carboniferous Lublin and Huczwa–Terebin Formations. Total thickness of these complexes was found to be 1107.5 m in Busówno IG-1 well. Average (of 106 samples) effective porosity is 5.77%. Average (of 58 samples) horizontal permeability is equal to 17.34 mD and average (of 111 samples) vertical permeability to 10.11 mD. Permeability results have been frequently expressed as <1 or <0.75 mD. Since the upper limit has been adopted to calculate the average, its value should be considered as inflated.

The Lublin Formation has the worst sealing properties of all of the above complexes, inflating average permeability and effective porosity values stated for all the complexes combined. Despite their worse sealing properties comparing to the Upper Silurian rocks, these formations may serve as a spare of sealing, should the Silurian complex fail.

Fault zones

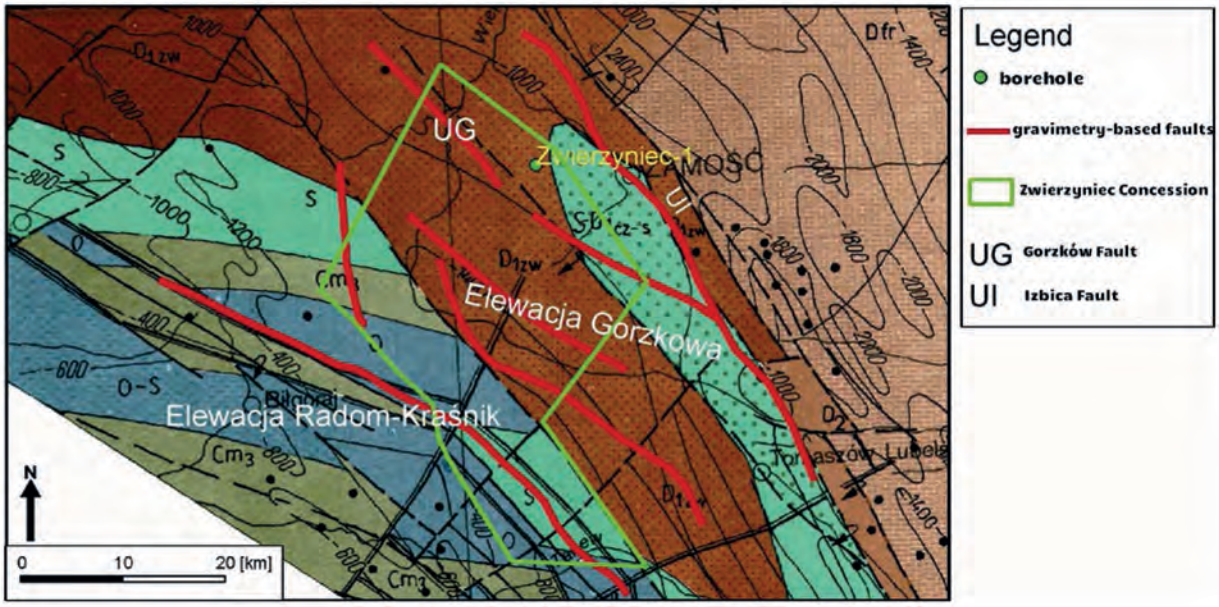
Considering good sealing properties of Upper Silurian beds, the only question is whether they are continuous at faults and whether the fault zones are tight. These issues have been investigated in two test sites, in the proximity of the Zwierzyniec-1 and Syczyn OU-2K wells.

Zawada Test Site

At Zwierzyniec-1 well, the prospective shale complex is located in Ordovician top and Silurian bottom. Since information on the faults occurring in the proximity of the well are inconsistent, the worst case scenario has been adopted: the nearest Gorzkow Fault is located 2.5 km SE and the Izbica Fault 2.5 km NE of the fracture stimulation interval (Fig. 3.9). At a relatively constant longitudinal horizontal stress direction in the Lublin Region, hydraulically induced fractures will propagate diagonally to both fault zones. This will add about 3 km to the clearance from the fault zones. Normally, a successful fracture stimulation procedure covers an area of 100–200 metres from the well. In the case of unsuccessful operation, when fractures tend to propagate along a natural master fracture, that distance may reach up to 1 km from the well (Bennet et al., 2006). Therefore, in no event fracture stimulation may result in penetration of the hydraulically induced fractures into the local main fault zones.

Faults adjacent to Zwierzyniec-1 well are probably Carboniferous thrusts formed in the regime of reverse faulting. Accordingly, the faults are not adjusted to the existing stress field and as such should not be reactivated at present.

All of the aforementioned arguments, based on scant data available for the area of Zwierzyniec-1 well, suggest that hydraulic fracturing of Ordovician and lowermost Silurian shales cannot result in fracturing fluid or gas migration to commercial aquifers.



UG – Gorzkow Fault, UI – Izbica Fault.

Fig. 3.9. Zwierzyniec 1 well location on geological/structural map of the Devonian (Żelichowski, 1982) and faults interpreted from the gravimetric map presented in Annex 2 (Chevron, 2012).

Syczyn test site

Interpretation made under this Project does not support the existing tectonic model for the area of Syczyn OU-2K well. A NE-SW fault located approx. less than 1 km from the well, as shown on the maps (Pożaryski, Dembowski, 1983), was not found by seismic surveys (Fig. 3.10). On the other hand, two uncharted fault zones have been interpreted: the WNW-ESE Syczyn fault zone striking longitudinally with regard to theelongation of the Lublin Basin at a distance of more than 3 km NE of the Syczyn OU-2K well. Small vertical offset of the fault zone, both in the lower Paleozoic and clastic Carboniferous, does not pose a formation unsealing risk. A fault zonestriking ca transversally with regard to the previous fault(of unknown precise orientation, as detected by only one 2D seismic line) is located at the same distance SE of the well. This fault zone has a much more extensive offset within the lower Paleozoic that may compromise the main Upper Silurian sealing complex. Moreover, an aureole of fractures and small faults, undetected by seismic profiles, is likely to surround the zone. As this transversal dyfault dies out at the Carboniferous bottom, that zone should be effectively sealed from the top by the approx. 700 m thick Carboniferous complex. Potential reactivation of that zone would be of a low magnitude and is not expected to contribute to the unsealing of the Carboniferous complex.

Considering a significant distance between the well and both fault zones, the induced fractures are not expected to get close to the fault zones, especially that the horizontal leg will not be longer than 2 km. This conclusion is subject to modification on establishing a precise orientation of the transversal fault.

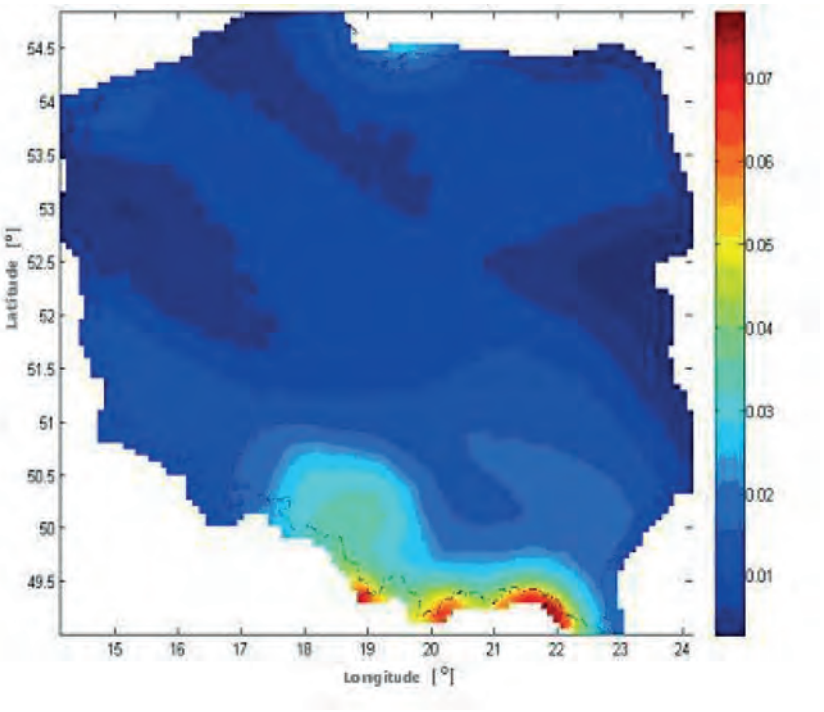
From the structural point of view, none of the fault zone may represent a risk of fluid migration from the lower Paleozoic complex to commercial aquifers, although the properties of the perpendicular fault and its Carboniferous sealing must be firmed up.

continuous red line – the main Syczyn fault
dotted red line – fault perpendicular to the main fault
dashed red line – transverse fault
yellow and thin black lines – seismic lines
black lines – other faults

Fig. 3.10. Approximate location of faults near the Syczyn OU-2K well shown on geological map (Pożaryski, Dembowski, 1983).

3.3.3 Natural seismic hazard in the surveyed area

Pomerania is among the least seismically active regions in Europe. No seismic events have been instrumentally recorded in the past 100 years or reported by historical sources over the last 1000 years (Guterch, 2009). Epicentres of the nearest earthquakes that are perceptible at the ground surface are located more than 100 km away of the surveyed areas. Also in the Lublin region the risk of earthquake occurrence is minimal and no seismic events have been reported fram that region. However, downhole logging data suggest that the risk in the Lublin region is somewhat higher than in Pomerania, insofar as long breakout profiles in drilling wells indicate much higher differential tectonic stresses. In Pomerania, short breakouts occur occasionally and out of the fracture stimulated complexes.



Colour scale – acceleration expressed as a fraction of gravitational acceleration [g]

Fig. 3.11. Seismic hazard map showing potential intensity of ground vibrations that is not expected to occur in a period of 100 years with 90% probability (according to J. Trojanowski, in PGI-NRI, 2014).

The minimum seismic hazard in the surveyed Pomerania and Lublin region is shown on Fig. 3.11 as acceleration of ground vibrations that are with 90% probability will not occur in the next 100 year. This is the latest seismic risk analysis for Poland, intended for major infrastructural projects, in particular nuclear power plant location (PGI-NRI, 2014). The map shows that the eartquakes expected to occur in the surveyed areas should not generate ground vibrations of more than 0.02 g. Such earthquakes are safe to power plants, as standard structures resist shocks below 0.1 g, while the latest structures are capable of withstanding 0.3 g. However, it should be kept in mind that these statistics are based on scarce data and the seismic risk is governed by the rules of probability. Therefore, it can be stated that a devastating earthquake cannot be ruled out with absolute certainty, but the probability of its occurrence is minimal. Concluding, in light of available information nothing suggests that any fracturing-induced shocks may represent a risk to the local residents or infrastructure facilities, be it in Pomerania or the Lublin Region.

3.4 Hydrogeological conditions

Hydrogeological patterns of the analysed survey areas reflect primarily changes in regional geology of Poland. In the Lublin Region, aquifers are located mainly in fractured and fractured-porous media. Groundwater dynamics are there quite different from porous media that typically occur in the Polish Lowlands. Another pattern specific to the Lublin Region is a widespread occurrence of aquifers perched on the weathered mantle of carbonate rocks. In the north of Poland, a complex system of aquifers developed in the sediments of all glaciation stages and frequently subjected to glaciotectonic deformations, is characteristic of early post-glacial landscape.

Accordingly, the conditions of aquifer occurrence are contingent on the depth to the top of main commercial aquifers (MCA), the thickness of the overlying poorly permeable rocks (or on the absence thereof), as well as on the co-occurrence of commercial (CA) and other, frequently top aquifers (TA). According to the classification adopted by Hydrogeological Map of Poland (1:50 000)

"Top Aquifer – Occurrence and Hydrodynamics", if the top aquifer or a set of top aquifers meets the adopted thickness, water transmissivity and potential productivity criteria, while serving as the key water supply source of a dominating range and adequate capacity, then it is at the same time attributed to main commercial aquifers (TA=MCA). The presence or absence of that identity, combined with occurrence of perched aquifers, determines the variability of hydrogeological conditions in the test areas established in the proximity of the drill sites. Moreover, the presence of perched aquifers slows down the rate of precipitation infiltration and by the same delays the time of potential pollutant penetration into the top aquifer. Natural resistance of the groundwater to contamination also depends on geology of particular regions, location in hydrodynamic-geomorphological zones and on the layout of total piezometric pressure heads in the aquifers. If the drill site is located near the natural drainage base, the main commercial aquifers are potentially protected hydrodynamically by piezometric pressure stabilization at a datum higher than that of the overlying top aquifer table. Moreover, migration path of potential contaminants is relatively short, if the source of pollution is located near the drainage base. The aspects of groundwater circulation in different hydrogeological media should be considered in investigations of vulnerability to potential contamination from unconventional oil and gas prospection and exploration operations. Filtration rate is higher in karst fractured than porous media, but the groundwater flow is closely dependent on the presence and location of fractures in the rock mass.

The above considerations on the potential migration of contaminants from ground surface would be no longer valid in the event of a sudden failure in annular or external casing cement integrity during hydraulic fracture stimulation operations. In that case, geology-controlled water filtration rates in the aquifers and well location in a hydrodynamic-geomorphological zone would be decisive to hydrodynamics. However, no such event has been reported during the studies.

An overview of hydrogeological conditions prevailing in particular unconventional oil and gas exploration/appraisal sites is presented below.

Lubocino Test Site

The drill site is located in the Żarnowiec High Plain, a regional recharge area, from which the groundwaters flow north- and westward with the trough of Żarnowieckie Lake, Putnica ice-marginal valley and coastal lowlands as drainage base.

Two perched Quaternary aquifers (PA-I and PA-II) have been identified above the TA=MCA in the survey area. Depth to the water table of the top unconfined perched aquifer (PA-I) generally does not exceed 5.0 m b.g.l. (0.5-5.0 m b.g.l.). Shallow groundwater (PA-I) occurs permanently only in depressions of the ground. The aquifer also has been found (periodically) in isolated sand layers between boulder clays, at depths ranging from 1.0 to 8.0 m b.g.l. The thickness of these water accumulations in the zone of aeration ranges from 0.5 to 2.0 m. The extensive second perched aquifer (PA-II) was reached with a piezometer at a depth of 28.0 m b.g.l. The aquifer is approx. 20.0 m thick, with water flowing away radially from the drill site area west-, east- and northward. The aquifer is drained by a source located in a ravine situated west of the drill site. In the past, the water in the aquifer had been produced with now abandoned well at Lubocino school. The depth to the aquifer ranges from 10.0 to 35.0 m b.g.l. in the survey area and its thickness is variable (from 1.0 to 20.0 m). Filtration coefficient of perched aquifers is highly variable and ranges from1.0 x 10^{-4} to 5.0 x 10^{-6} m/s.

Top aquifer (TP) is built of Quaternary varigrained sands and gravels. The depth to its top is over 50.0 m in the moraine high plain area. Water table of that confined aquifer stabilizes at depths ranging from 5.0 to 50.0 m a.s.l, but locally the aquifer is unconfined. TA thickness, as measured within the high plain area, ranges from 6.0 to 20.0 m. The main Quaternary commercial aquifer (MCA) is 25.0–35.0 m thick and occurs at a depth of approx. 70.0 m b.g.l. in the survey area. Water table of that confined aquifer stabilizes at depths ranging from 15.0 to 40.0 m a.s.l, but locally the aquifer is unconfined. The top aquifer, which fails to meet the commercial aquifer criteria, is hydraulically interconnected with MCA. Near Lubocino, TA merges with MCA to form a single confined aquifer, reached in the drill site at a depth of 68.6 m b.g.l. (34.4 m b.s.l.). The bottom of that aquifer was found at a depth of 98.0 m b.g.l. Filtration coefficient ranges from 1.0 x 10^{-4} to 1.0 x 10^{-5} m/s.

Deeper aquifers have not been investigated in the Lubocino region. In light of regional hydrogeological studies it can be concluded that the Miocene aquifer is locally interconnected with the

Quaternary aquifer. The aquifer is sub-artesian and its water table stabilizes at 3.0 to 48.0 m a.s.l. The 5.0 to 20.0 m thick Oligocene aquifer is built of fine to medium grained quartz sands, frequently with an admixture of glauconite. The aquifer is sub-artesian or artesian with water table stabilizing at approx. 5.0 to 44.0 m a.s.l.

Stare Miasto Test Site

Two aquifers were identified in the Stare Miasto test site area. The top Quaternary aquifer carries groundwater (considered as top aquifer), as well as one or two intra-moraine levels having diversified parameters. The second aquifer is located in Paleogene formations. The top locally bilayered aquifer (TA), the main intra-moraine commercial aquifer (MCA) and an intra-moraine commercial aquifer (CA) were identified in immediate neighbourhood of the abandoned drill site. The water from the aquifer built of Oligocene sands is produced in the town of Dzierzgoń (a municipal water intake). These formations have not been investigated near the village of Stare Miasto, but considering a widespread distribution of the Paleogene aquifer across that region they are likely to form a commercial aquifer (CA).

In immediate test site neighbourhood, the top aquifer (TA) is composed of two locally hydraulically interconnected 6.0–8.0 m thick layers (glaciofluvial sands overlain by boulder clays of the Vistula glaciation and outwash sands on the ground surface). Outwash sediments are not found in places other than a depression located at Stare Miasto north of mine pits (abandoned one near the drill site and active one northwestward of the site), the drill site and north of it. Up to 5.0–10.0 m thick boulder clays deposited on the ground surface are underlain by 5.0 to 10.0 m thick sands (the aquifer). Within the erosional structure with sand and gravel pits, the aquifer sands were initially up to 18.4–20.0 m thick. The confined water table (measured during the survey) and the locally unconfined water table (pre-existing measurements made as part of sand and gravel reserves proving) are located at 3.5–7.9 m b.g.l. and 1.5–6.8 m b.g.l., respectively. The water in CA flows towards the abandoned pit and then northwestward to the local drainage base (Dzierzgoń River). According to model studies, filtration coefficient is equal to 2,3 x 10^{-5} m/s in immediate site vicinity.

The top of MCA, built of Eemian glaciofluvial sands and gravels, was found at depths ranging from 21.0 to 50.2 m b.g.l. in the drill site area. Average depth is equal to approx. 20.0. m. The water in that aquifer is produced from the interval of 27.0–46.0 with a well (now abandoned) located in the locality of Stare Miasto. The main commercial aquifer is isolated from the ground surface with an approx. 20.0 m thick package of boulder clays. The thickness of isolating rocks is reduced to approx. 10.0 m in immediate drill site proximity as a result of (most probably erosional) lowering of the boulder clay surface. The thicknesses of poorly permeable rocks located over the aquifer top are much higher towards the east, west and north, where they reach as much as 46.0 m. The groundwater flows towards the Dzierzgoń River valley. Confined water table, measured during the survey in a drilled well at Stare Miasto, is located at depths ranging from 2.1 to 2.6 m b.g.l. Filtration coefficient, as determined by test pumping of the well, is equal to 4.6 x 10^{-5} m/s.

According to regional studies, one more Quaternary (lower) aquifer is present in the survey area. The conditions of its occurrence have not been investigated in detail due to a lack of boreholes penetrating to that aquifer. The nearest ones are located in Kielmy, about 2.0 km away toward the east. Only one of them reached the top of that 6.0 m thick aquifer at a depth of 66.0 m b.g.l. Confine water table stabilizes at 4.4 m b.g.l. Regionally, the water in that aquifer flows to the north. The aquifer is highly isolated by an overlying complex of 57.5 m thick boulder clay complex documented at the rural water intake in Kielmy.

According to Hydrogeological Map of Poland at 1 : 50 000, sheet Dzierzgoń (0133) (Waluszko, 1998), the zone wherein Quaternary aquifers are no longer considered as commercial (suitable for development of collective groundwater supply systems), and are replaced by the Paleogene aquifer, starts immediately north of Stare Miasto and stretches as a narrow (on average 2 km wide) belt through the town of Dzierzgoń further to the north. The Paleogene (Oligocene) over 60.0 m thick water-bearing sands that occur at depths from 109.0 to 115.0 m have excellent hydrogeological parameters. Average filtration coefficient is 1.1 x 10^{-4} m/s. Average transmissivity reaches 550.0 m^2/24 h and well productivity is in the order of 180.0 m^3/h. Since the water in this aquifer is not produced south of Stare Miasto, it is there considered as a CA rather than main commercial aquifer.

Syczyn Test Site

There is only one combined Quaternary-Upper Cretaceous (TA=MCA) aquifer in that area. Despite the different reservoir characteristics, Upper Cretaceous and Quaternary sediments form a single hydraulically interconnected aquifer. In the drill site area, unconfined water table is normally found at a depth of up to 15.0 m b.g.l., or less than 5.0 m b.g.l. in river valleys. At the drill site it was recorded at 2.3–3.3 m b.g.l. The aquifer is recharged directly by infiltrating rainfall and the water flows away in northwestern direction. The valley of Wieprza River and its tributaries (Świnka River) is the drainage base. MCA thicknesses exceed 40.0 m in the survey area. In Cretaceous rocks (fractured medium), infiltration coefficient of 1.6 x 10^{-4} m/s is higher than in Quaternary sediments (3.5 x 10^{-5} m/s). The test site is located in the area of the Main Commercial Aquifer No. 407 (Lublin Basin–Chełm–Zamość Reservoir).

Wysin Test Site

The Wysin test site area is drained by the Wietcisa River, a left tributary of Wierzyca River in the Vistula River catchment area. Wietcisa flows in a wide peaty and land-improved valley having two predominant directions: latitudinal – in troughs and longitudinal – in gorges.

The test site is located within the proven Quaternary Main Commercial Aquifer No. 116 (Gołębiewo Intra-moraine Reservoir). Near Wysin, the Quaternary commercial aquifer includes three levels: top, Upper Quaternary and Lower Quaternary level. The local top level is associated with the sediments of river valleys. The level is of small thickness and low capacity, its water table is unconfined or has a slight piezometric pressure. It is locally interconnected with the Upper Quaternary level – the main commercial aquifer.

The Upper Quaternary main commercial aquifer is associated with the sediments of North Poland glaciation stages. It occurs at depths of 15 to 50 m under the cover of clays, only in the valley of Wietcisa the depth to the aquifer is 5–15 m. The thickness of the aquifer ranges from 20 to 40 m in the test site area and from 10 to 20 m south of it in the Wietcisa River valley, at transmssivities in the order of 200–500 m^2/24 h and 100–200 m^2/24 h, respectively. Potential well productivities range from 50 to 70 m^3/h, but are less than 30 m^3/h in the river valley. The aquifer is recharged primarily by rainwater infiltration with small contributions of lateral inflow and surface water courses. The water flows southward and southeastward towards the valley of Wietcisa River, which along with its tributary Rutkownica is the local drainage base for the groundwater. The water table is usually confined.

The Lower Quaternary level (CA) has been little investigated so far, on account of the capacity of the upper level. The sediments of the Middle and in places also South Poland Glaciation are the medium of this aquifer.

Both level are hydraulically interconnected with valleys and deeply incised glacial troughs as contact places. The lower level is recharged by water percolating from the upper level through a package of poorly permeable loams. The levels form a single aquifer with a similar recharge system, water outflow directions and share the same drainage base. Infiltration coefficients established for both levels at tg\he nearest water intakes (Wysin, Stary Wiec, Chrósty Wysińskie) range from 1.17 to 7.76 x 10^{-4}m/s.

Zawada Test Site

A single aquifer (TA=MCA) occurs in topmost Cretaceous (Maastrichtian) sediments at the Zawada test site. In high plain areas, several metre thick loess covers frequently overlie carbonate Cretaceous rocks. The loess cover is approx. 5.0 m thick at the Zawada test site. Rainwater infiltration condition vary depending on the type of rocks forming the topmost section of the geological profile. Rock debris that overlie the gaizes at depths of 1.0 to 4.0 m have good infiltration properties. Marl rocks and chalkstones are covered with poorly permeable weathered loams. The groundwater flows northward in the survey area. The Wieprz River and its tributaries (Łabuńka) are the base of drainage. The unconfined (locally confined) water table is usually found at depths inferior to 20.0 m b.g.l. in the test site area. In the nearest drilled well ("Presbet"), the water table penetrated at 18.0 m b.g.l. gets stabilized at 13.5 m b.g.l. The aquifer is over 40 m thick and filtration coefficient is equal to 9.6 x 10^{-5} m/s. In two water wells drilled out in the drill site perimeter, each 75.0 m deep, the water table was found at 15.35 m b.g.l. The aquifer is more than 59.65 m thick. The productivity of each well was established by pumping test at 8.91 m^3/h x 1m and the filtration coefficient was found to be 1.88 x 10^{-5} m/s. In the test site area, potential productivities of typical water wells range from 30 to 50 m^3/h and transmis-

sivities are in the order of 200–500 m^2/d. The test site is located within the Main Commercial Aquifer No. 407 (Lublin Basin – Chełm–Zamość Reservoir).

Łebień Test Site

TA is at the same time MCA at Łebień test site area. The Quaternary sub-till level is the main commercial aquifer. It is built of 5.0 to 40.0 m thick varigrained sands and gravels of the Middle and North Poland glaciation stages, which are isolated from the ground surface with 3.0 to 20.0 m thick boulder clays. The confined (locally unconfined) water table gets stabilized at depths ranging from approx. 30.0 m a.s.l. to 100.0 m a.s.l. In the drill site area, the water table is unconfined and occurs at 60.24 m a.s.l. (Wolski, 2010), the commercial aquifer is located at depths ranging from 10.0 to 20,0 m b.g.l. The depth to water table, as measured at the drill site from December 2013 through July 2014, was approx. 14.0–15.6 m b.g.l. Model-based filtration coefficient is equal to approx. 16 m/d (1,85 x 10^{-4} m/s).

Two commercial Neogene and Paleogene aquifers are present in the survey area. Two Neogene levels are located in Miocene fine-grained sands of which thickness is not in excess of 40.0 m. The datum of the upper level is 0.0–75.0 m a.s.l. and that of the lower one ranges from 60.0 to 100.0 m a.s.l. These levels are of a low capacity and are produced solely in the Łeba ice-marginal valley and its boundary zone (beyond the survey area), where the water is usually produced from a combined Quaternary-Miocene aquifer. The Paleogene level occurs in 10.0 to 25.0 m thick fine-grained glauconite Oligocene sands. The depth to that level is 40.0–80.0 m a.s.l. (Paczyński, Sadurski, ed., 2007).

The drill site is located out of the range of Main Commercial Aquifers. The water table contour at the drill site area indicates a major influence of the Łeba River and its tributaries as the base of drainage. A gentle hydraulic slope and a high transmissivity at a low flux rate are visible (Prussak, 1998). Regionally, the waters flow southward and southeastward (PGI-NRI, 2011).

Gapowo Test Site

The test site is located within a moraine high plain which is the recharge area for the main commercial aquifer. The groundwater flows southeastward from the high plain and the outwash plain situated southeast of the site towards the local drainage base (Raduńskie Górne Lake in a deeply incised post-glacial trough).

A top aquifer (TA) with highly variable conditions of occurrence has been documented at the rolling post-glacial high plain in immediate drill site proximity (Jankowski, Kowalewski, 2008). Discontinuous 2.0–3.0 m thick sand layers, most frequently in the form of lentils, within the boulder clays are locally used as water supply sources. They occur at depths ranging from approx. 3.0 m to 6.0 m b.g.l. and are drained via local network of ditches to the local water courses. The drainage network is particularly extensive near the lakes and in outwash sand plains. The water contained in sand intercalations within the boulder clays is produced using hand-dug wells for commercial purposes.

Near Klukowa Huta and further to the south and southeast, the regionally uniform main commercial aquifer (the second intra-moraine aquifer) is composed of two separate layers of glaciofluvial formations of the Warthe and Oder Stages of glaciation. Regional layout of the two layers indicates that they are hydraulically interconnected with each other. The top of the upper layer falls from approx. 120–125 m a.s.l. in the north to approx. 110 m a.s.l. The layer peters out approx. 1.5–2.0 km south and southeast of Klukowa Huta ant its top falls accordingly. The layer is approx. 8–10 m thick. The lower layer that forms the Main Commercial Aquifer (MCA) is continuous throughout the region. In the drill site area, the main commercial aquifer (MCA) and the upper layer form a fossil valley with sharply defined boundaries. The top of the upper MCA layer falls from approx. 110 m a.s.l. in the north (Widna Góra), 92–93 m a.s.l. (Mściszewice), 95.6 m a.s.l. (126.0 m b.g.l.) at Klukowa Huta to 103.8 m a.s.l. (Stężycka Huta) and approx. 80–82 m a.s.l. at Stężyca. The thickness of the lower layer is in excess of 12 m in Żuromino (not drilled through), 14.4 m at Stężycka Huta and 20 m at Klukowa Huta. In immediate neighbourhood of the investigated area, the top of the upper MCA segment (associated with a fossil valley) is located at 115.6 m a.s.l. (106.0 m b.g.l.) in Klukowa Huta and 122 m a.s.l. (81.0 m b.g.l.) in the drill site area. The two layers combined form an aquifer of which thickness ranges from 40.0 m at Klukowa Huta to more than 50.0 m in the drill site area. Filtration coefficient of the MCA layers ranges from 3.9 x 10^{-4} to 1.5 x 10^{-5} m/s. Average transmissivity ranges from 100 to 200 m^2/24h, and potential productivity is in the range of 40 to 60 m^3/h (Lidzbarski, 2000). Confined

water table of that aquifer gets stabilized at 22.0–43.0 m b.g.l. in the investigated area and falls towards the trough of the Raduńskiego Górne Lake. The aquifer is fully isolated by the complex of impervious boulder clays of which thickness above the aquifer top ranges from a dozen to several tens of metres (76.0–94.5 m) or locally is in excess of 100.0 m. In the outwash plain area, along the trough of Raduńskiego Górne Lake, the aquifer is no longer considered as main commercial aquifer and is attributed to CA.

Discontinuous layers that cannot be attributed to commercial aquifers occur above the main commercial aquifer. Their thicknesses vary and range from 6.1 m to 9.0 m. Younger glaciofluvial sediments of the Warthe and Baltic glaciation form the first intra-moraine aquifer which is considered as the MCA in the area of Radunia glacial trough. The thickness of the aquifer ranges from 10.5 m (Żuromino), 12.5 m (Stężyca) to 14.0 m (Borucino). The top of the aquifer was found at depths ranging from 35.0 to 50.0 m b.g.l., respectively. The aquifer is poorly isolated in immediate proximity of the lake, but further away it is covered by an up to 15.0 m thick complex of boulder clays. Filtration coefficient of that aquifer is in the order of 1.7–3.5 x 10^{-4}, water transmissivity ranges from 150 to 700 m^2/24 h/km^2, and its potential productivity is in excess of 40 m^3/h (Lidzbarski, 2000). The confined water table is found at depths ranging from 20.0 to 27.0 m b.g.l. and tends to fall towards the Raduńskie Górne Lake.

The top aquifer (TA) is situated in an outwash plain that stretches mainly eastward of the trough of Raduńskie Górne and Stężyckie Lakes. This aquifer has been little investigated so far, as due to the deeply incised trough of the Raduńskie Górne Lake the aquifer is largely absent in the outwash plain area. The outwash plain aquifer is frequently interconnected with the first intra-moraine aquifer in the proximity of the lake. The unconfined outwash plain aquifer is built of varigrained and fine-grained sands. Its unconfined water table was found at depths ranging from 2.2 to 15.4 m b.g.l.

3.4.1 Natural resistance to contamination

Natural resistance of the analysed aquifers to contamination is controlled by the degree of isolation with poorly permeable rocks and hydrogeological conditions that are contingent on actual location in a given geomorphological-hydrodynamic zone of the groundwater circulation system. A typology based on the superposition of aquifers in the geological profile was considered in the overview below.

Lubocino Test Site

The shallowest groundwater is contained in the topmost perched aquifer (TA-I). The depth to the water table ranges from 0.5 to 5.0 m b.g.l. As a consequence, these waters are extremely vulnerable: potential contaminants from the ground surface may reach them after a few months.

The second perched aquifer is poorly isolated, too. In the test site area, the boulder clay cover at the ground surface is a few metre thick. The migration time of pollutants, as calculated based on verified data according to "*Methodology guidance for the development of GIS database information layers for the Hydrogeological Map of Poland, scale 1:50 000 „Top aquifer vulnerability to pollution and water quality"* is approx. 11 years. Topsoil removed at drill site development stage was not considered in the calculations. Therefore, the actual time of pollutant migration to to the aquifer may be as short as less than 8 years.

According to Hydrogeological Map of Poland, scale 1:50 000, sheet Sławoszyno (0005) (Sierżęga, Chmielowska, 2000), the degree of MCA vulnerability is very low, considering the presence of TA and isolating interbeddings in the drill site area (average isolation, i.e. 15–50 m thick boulder clays). The risks to commercial aquifer was found to be low and the time of pollutant migration was estimated at roughly 30–50 years. According to data provided by recently drilled hydrogeological wells, the thickness of isolating strata in the MCP overburden is much reduced, significantly accelerating the migration of potential pollutants to the commercial aquifer. Therefore, MCA vulnerability has been estimated as high. The depth to aquifer is more than 50 metres, but isolation with a several metre thick boulder clay complex is only partially effective. Accordingly, the time of water infiltration to the aquifer was established at 14 years for the investigated area.

The distribution of and depth to perched aquifers occurring in sand lentils within bouldre clays have no effect on the final vulnerability of TA=MCA (high vulnerability – time of potential pollutant migration: 5–25 years).

Stare Miasto Test Site

The top aquifer (TA) situated in the moraine high plain is poorly isolated, as the thickness of overlying boulder clays is small. The drill site is located at the margin of a local erosional structure where sand and gravel have been extracted. In its central part, the aquifer is practically not isolated and the intra-moraine aquifer layers occur directly beneath outwash sands with outcrops in the Dzierzgoń River valley. In the valley, a deeply incised erosional structure of the TA is in hydraulic contact with MCA forming a joint unconfined aquifer. In immediate drill site neighbourhood, some degree of isolation slightly increases the time of infiltration rainfall water percolation. According to digital hydrogeological model, it takes 70 days for rainfall water to infiltrate through the zone of aeration in the area of the abandoned drill site. Therefore, the top aquifer is highly vulnerable to pollution from the ground surface.

According to Hydrogeological Map of Poland, scale 1:50 000, Dzierzgoń sheet (Waluszko, 1998), MCA is partially isolated in the test site area (15–50 m thick poorly permeable rocks above the aquifer). Therefore, the degree of main commercial aquifer vulnerability was determined as low. Natural resistance of the aquifer to migration of pollutants from the ground surface is strengthened by the stabilization of MCA's confined water table above that of TA, which is characteristic of drainage zones. However, in immediate drill site neighbourhood the degree of protection is much lower due to the presence of erosional structure with reduced thicknesses of poorly permeable strata, which are practically absent in the Dzierzgoń River valley. The hydraulic contact of TA and MCA in immediate drill site proximity makes MCA highly vulnerable due to the lack of isolation.

Commercial aquifers are fully isolated (over 50 m thick poorly permeable rocks in the aquifer overburden) in the exploration area and their degree of vulnerability is very low.

Syczyn Test Site

The main commercial aquifer in the analysed area is poorly isolated or not isolated at all. Moreover, considering its relatively shallow water table the degree of aquifer vulnerability to pollution from ground surface is believed to be high and very high (Zezula, Pietruszka, 1998; Krajewski, Olszewski, 1998). The time of water infiltration through the zone of aeration (varigrained sands, silts and silty sands) to the groundwater table, calculated using the digital hydrogeological model, is equal to 107 days. This means that potential ground surface pollutants may reach the aquifer in a period of about 3 months.

Wysin Test Site

According to Hydrogeological Map of Poland, scale 1:50 000, Skarszewy sheet (Szelewicka, 1998), the MCA is low vulnerable to pollution, taking account of TA presence that delays migration of pollutants and occurrence of isolating interbeds in the drill site area (average isolation, i.e. 15–50 m thick boulder clays). In immediate drill site proximity the degree of vulnerability was specified as low. Vulnerability was found to be average in the valley of Wietcisa River with a small package of underlying loams and in the region of Wysin and Stary Wiec, where facilities that potentially may represent a risk to the groundwaters are located. Model studies made under this project included an assessment of groundwater vulnerability to pollution by calculating the time of (potentially polluted) water infiltration through the zone of aeration. The calculations are based on the assumption that the (interpolated) depth to aquifer top is 27 m and that sands and boulder clays account for approx. 7 m and 20 m of the profile, respectively. At these assumptions, the time of vertical migration through the zone of aeration is estimated at 4.3 years.

Zawada Test Site

The Cretaceous aquifer is recharged primarily by direct rainwater infiltration to the aquifer (through the outcrops Upper Cretaceous rocks) and by water percolation through permeable rocks of the Quaternary cover. In immediate drill site vicinity, the aquifer is overlain by loess and weathered marls of a small thickness (14.0 m – reported from wells drilled out in the drill site perimeter) and poor isolation properties. As part of groundwater vulnerability to pollution assessment, the time of (potentially polluted) water infiltration through the zone of aeration was calculated. The approximate time of percolation through the zone of aeration is 725 days. This means that potential

ground surface pollutants may reach the aquifer after a period of about 2 years. Accordingly, the degree of MCA vulnerability was determined as very high (Czerwińska-Tomczyk, Sadurski, 1998).

Łebień Test Site

According to an assessment based on "*Methodology guidance for the development of GIS database information layers for the Hydrogeological Map of Poland, scale 1:50 000 „Top aquifer vulnerability to pollution and water quality"*, top aquifer vulnerability to pollution is average. Hindered infiltration areas were not found in the surveyed region. On the other hand, there is a clear correlation between the depth to TA and natural vulnerability. Top aquifer resistance to pollution tends to increase with increasing thickness of the zone of aeration. In the drill site area, the aquifer is isolated by a complex of boulder clays. Its thickness varies from 3.0 to 20.0 m, and is as small as 3.0 m near the pad. The potable groundwater occurs at a relatively small depth (approx. 14.0–15.6 m b.g.l.). Migration time of potential pollutants from the drill site are to the aquifer is 3.3 years (1200), considering local hydrogeological conditions. Moreover, model studies made it possible to establish illustrative times for migration of potential pollutants to the nearest active groundwater intakes, MCA, water courses, water reservoirs located in the approximate water flow direction:

- privately-owned water intake, located 2.1 km towards the south – as a minimum 5.6 years (2040 days)
- municipal water intake Obliwice (2 wells), located 2.9 km towards the south – as a minimum approx. 6.4 years (2360 days),
- water course – Kisewska Struga flowing 5.0 km southeast of the drill site – as a minimum approx. 8.7 years (3200 days),
- the nearest water reservoir located 1.5 km southeast of the drill site – as a minimum 5 years (1840 days),
- MCA Reservoir No. 107 "Łeba River Ice-Marginal Valley" situated 7 km southeast of the drill site – as a minimum 11 years (4000 days).

Gapowo Test Site

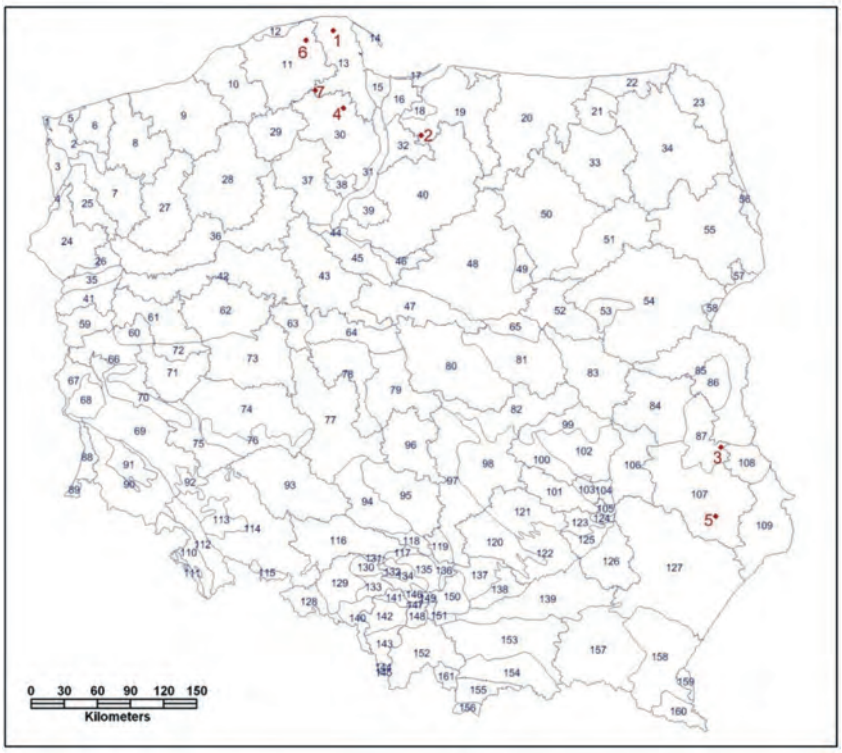
The lower intra-moraine MCA is at risk of pollution. The upper intra-moraine level is not continuous, as is the top aquifer (TA) with different patterns of occurrence in sand layers and intercalations within boulder clays at the ground surface. The intra-moraine layers that form commercial and main commercial aquifers in the high plain area are little or very little vulnerable to anthropogenic pollution (Witczak, 2011). They are tightly isolated with a boulder clay complex that is over 100.0 or up to 50 m thick (the second and the first intra-moraine level, respectively). In order to assess in detail MCA (the second intra-moraine layer) vulnerability to ground surface pollution in the drill site area, the time of (potentially polluted) water infiltration through the zone of aeration was calculated. The approximate time of water percolation through the zone of aeration is 2670 days. This means that potential ground surface pollutants may reach the aquifer after a period of about 7 years. Accordingly, the aquifer is highly resistant to pollution and its vulnerability is very low (Lidzbarski, 2000).

3.4.2 Water availability and quantitative security of resources

Water consumption in technological processes, hydraulic fracture stimulation in particular, is an important aspect of environmental impact from drill site operations. It is vital to assess the effects of operations on the status of available groundwater resources and whether they are likely to have adverse effects on water availability to other users, including in particular the local residents. Having regard to potential impact and pressure from the operations on uniform parts of groundwater bodies (UPGB), which under Directive 200/60/EC of the European Parliament and of the Council establishing a framework for Community action in the field of water policy (the so-called Framework Water Directive), and the Water Law (2012 Journal of Laws, Item 145) implementing the Directive, is the main unit used in assessments of quantitative and chemical status of groundwater, the operations have been assessed considering these units. Test site locations are presented against the background of UPGB on Fig. 3.12. The boundaries and the resources of particular UPGBs are shown according to the exist-

ing subdivision into 161 UPGBs, using the report on delivery of projects by National Hydrogeological Survey, project no. 19: "The determination of recorded offtake from uniform parts of groundwater bodies, including an update on the quantitative status of groundwater in UBGBs that are at risk of a failure to achieve the environmental targets", dated March 2014 (Table 3.2). Information obtained from the Database of available groundwater resources, as maintained by PGI-NRI, was used in the analysis. Water offtake records have been tabulated on the basis of information provided by Local Assembly Speakers and mining plants.

In order to assess potential effects on water supply to other users, the volumes of water used have been compared with the available water reserves of particular UBGBs (Table 3.2). The worst scenario (the groundwater abstracted from on-site wells or sourced from the local water supply systems) was adopted. In reality, depending on location, the water from on-site wells, groundwater delivered by local water supply systems and surface water (Stare Miasto test site) was used.



Test site location

1– Lubocino, 2 – Stare Miasto, 3 – Syczyn, 4 – Wysin, 5 – Zawada, 6 – Łebień, 7 – Gapowo

Fig. 3.12. Test site location within Uniform Parts of Groundwater Bodies (UPGB).

Table 3.2. Available groundwater resources of relevant uniform parts of groundwater bodies

No. of UPGB	unit	11	13	19	30	87	107
Test site		**Łebień**	**Lubocino, Gapowo**	**Stare Miasto**	**Wysin**	**Syczyn**	**Zawada**
UPGB surface area	(km^2)	4097.2	2818.2	3996.5	3942.8	1841.5	5326.2
Resources available for management (RAM) as of end 2012*	(thousands of m^3/year)	261 035	138 313	139 912	149 939	98 793	270 308
Factors materially affecting the UPGB resource estimation error, depending on its size and presence**: LAKE – lakes; VAL – valleys;	–	LAKE	LAKE	LAKE	LAKE	VAL	
Resource reduction for factors materially affecting the UPGB resource estimation error, **rr (–)**	–	0.8	0.8	0.8	0.8	0.8	0.95
Rr-reduced resources available for management **(RAM_min)** as of end 2012	(thousands of m^3/year)	208 828	110 650	111 930	119 951	79 034	256 792
Recorded groundwater takeoff in 2012	(thousands of m^3/year)	18 289	54 489	8 193	12 576	6 665	36 820
Water drained from active mines in 2012	(thousands of m^3/year)					5 893***	6 500****
Total recorded groundwater takeoff in 2012 (from intakes and mine drainage systems)	(thousands of m^3/year)	18 289	54 489	8 193	12 576	12 558	43 320
Percentage of available resources used – Total takeoff/RAM	**(%)**	7	39	6	8	13	16
Percentage of available resources corrected for rr – Total takeoff / RAM_min	**(%)**	9	49	7	10	16	17

* *based on National Hydrogeological Survey's database of available resources (PGI-NRI)*

** *based on Herbich et al. 2007: "Study on pressures and impacts of anthropogenic pollutants by uniform parts of surface and ground water bodies, intended for development of action programmes and water management plans",. The report. Environment Ministry, PGI, Warsaw*

*** *Bogdanka Coal Mine*

**** *Rejowiec Mine, limestones and marls for the cement industry*

3.5 Nature conservation

According to Art. 6.1 of the *Nature Conservation Act of 16 April 2004* (2013 Journal of Laws, Item 627, as amended), nature conservation forms are: Natura 2000 sites, national parks, nature reserves, scenic parks, protected landscape areas, ecological use areas, nature/landscape complexes, landmarks of nature and documentation sites. The conservation of particular sites is additionally strengthened by the protection of plant, animal and fungi species that occur in areas that are intended for drill site development.

As part of this project, each drill site location has been analyzed for potential conflicts with environmentally valuable areas, as defined by the aforementioned Nature Conservation Act. As a result of the analysis it has been established that:

- Lubocino drill site is located within the boundaries of the "Puszcza Darżlubska" Protected Landscape Area;
- Syczyn drill site is located within the boundaries of the Chełm Protected Landscape Area;
- Stare Miasto drill site is located in immediate neighbourhood of the Dzierzgoń River Protected Landscape Area;
- Gapowo drill site is located in the buffer zone of the Kaszuby Scenic Park.

Wysin, Łebień and Zawada drill sites are not located within or in immediate neighbourhood of environmentally valuable areas. Drill site locations with regard to protected areas of the Pomeranian Provinces are shown on maps attached as Appendices 2.1, 2.2, 2.3 and 2.4 hereto.

Regulatory requirements concerning Lubocino and Syczyn drill site location within the boundaries of protected area are presented below.

Lubocino Drill Site

An analysis of Lubocino drill site location with respect to environmentally valuable areas has revealed that the Lubocino test site is located in an area of exceptional environmental value. The Lubocino drill site is located within the "Puszcza Darżlubska" Protected Landscape Area. The following ecological use areas, established by Pomeranian Province Head's Regulation No. 163/99 of 16 November 1999, are situated in drill site proximity: Świecińska Topiel rush community (size: 1.25 ha), 1.7 km northeast of the site; Księża Łąka meadow and fen (size: 3.8 ha) 2.1 km south of the site; and Witalicz Lake (size: 8.51 ha) 2.7 km northeast of the site. The Natura 2000 PLH220029 "Trzy Młyny"site (size: 765.9 ha) is located about 3.3 km northeast of the drill site. This area is partly covered by the nature reserve "Źródliska Czarnej Wody" and by "Puszcza Darżlubska" Protected Landscape Area. Several protected areas, including Natura 2000 – PLH220090 "Opalińskie Buczyny", PLB 220007 "Puszcza Darżlubska", PLH220019 "Orle"special protection areas, "Pradolina Redy – Łeby" Protected Landscape Area or the "Źródliska Czarnej Wody" nature reserve, are located at a distance of more than 5 km from the drill site.

Considering a wealth of various nature conservation areas in drill site neighbourhood and its immediate proximity, the conditions for delivery of drill site operations are governed directly by the decision of Regional Director for Environmental Protection in Gdańsk of 14 March 2012 (Ref.: RDOS-Gd-WOO.4210.53.15.2011.ER) on environmental preconditions for the project "Oil and gas prospection and exploration in the WEJHEROWO 4/2009/p Concession area", which imposed the obligation to protect the environmental values. Paragraph 2.3 of the Decision states that "drilling locations and drill site development plans (including locations of freshwater and flowback fluid tank) shall be determined in consultation with Regional Director for Environmental Protection in Gdańsk, upon environmental inventory taking and an assessment of the effect of drill site location on the area within the range of impact therefrom". In accordance with Paragraph 2.25: "areas of occurrence of species that are subject to zonal protection should be excluded from the area of the planned drilling operations". In 2012, the Operator commissioned an environmental inventory of species and natural habitats in the concession area. As a result of inventory taking one amphibian species was identified in the planned drill site: the sand lizard. In accordance with Appendix 1 to Environment Minister's Ordinance of 12 October 2011 on the protection of animal species (Journal of Laws No. 237, Item 1419), sand lizard is subject to strict protection and it is prohibited to destroy knowingly its habitats, stay areas, nests and other shelters (§7.6,7,8 of the Ordinance). Therefore, in order to be able to develop

the project site and deliver drilling operations, including hydraulic fracture stimulation, the Operator obtained from Regional Director for Environmental Protection in Gdańsk the Decision of 6 June 2012 (Ref.: RDOS-GD-PNII.6401.41.2012.EK.1) that consented for destruction of habitats, stay areas, nests and other shelters by cutting trees and shrubs and delivery of earthworks using heavy construction equipment. Moreover, the Operator obtained from Regional Director for Environmental Protection in Gdańsk the Decision of June 2012 (Ref.: DOP-OZGIZ.64.01.8.2012.dł) which allowed for deliberate frightening or disturbing of the following animal species: sand lizard, skylark, red kite, western yellow wagtail, corn bunting and crane. All the operations are to be delivered under environmental supervisions and the Operator shall submit to Directorate General of Environmental Protection (DGEP) information on the use of permits by 15 January of each permit validity year with the final information to be submitted by 15 January 2017. Reports on delivery of environmental supervision should be appended to the information. The permits shall remain valid until 31 December 2016. The Operator has complied with the obligation to DGEP environmental supervision reports on the operations.

Syczyn Drill Site

An analysis of Syczyn drill site location with respect to environmentally valuable areas has revealed that the Syczyn test site is located in an area of exceptional environmental value. The site is located with the boundaries of the Chełm Protected Landscape Area. The Natura 2000 – Ostoja Poleska PLH060013 special protection area, of which boundary partly corresponds with that of an exclave of Polesie National Park, is located about 6 km north of the site and the Dobromyśl PLH 060033 is situated approx. 7 km southwest of the site. A vegetation and aquatic reserve (Świerszczów Lake) is located approx. 6.5 km northwest of the Syczyn drill site.

Considering the presence of various nature conservation areas in drill site neighbourhood and its immediate proximity, the conditions for delivery of drill site operations are governed directly by the decision of Wierzbica Commune Head, dated 17 October 2012 (Ref.: Bd.3.6220.5.2011) on environmental preconditions for the project: *"Changes in the scope of works and in the term of Concession 28/2007p for crude oil and natural gas prospection and exploration in the Wierzbica Concession area (parts of concession blocks 298,299,319), as awarded to PKN ORLEN S.A. by the Minister of the Environment on 30 October 2007 października 2007 r., including the Decision of 28 April 2010 on concession transfer to ORLEN Upstream Sp. z o.o. – operations consisting of drilling wells up to 1000 m deep"*. The decision provides for the necessity to protect precious environmental values. In accordance with the aforementioned decision, all activities associated with drill site development and operation should follow prohibitions and injunctions that apply to environmentally valuable areas, including animal and plant species that occur therein. Moreover, documents on drill site impact on the environment should be delivered to Regional Director for Environmental Protection in Lublin for the planned drilling locations prior to the beginning of field operations.

4. The Extent of Impact on the Environment and the Population

All potential detrimental effects of unconventional oil and gas exploration are tabulated in Appendix 3. An expanded version is presented below.

4.1 Noise

Test site monitoring for noise was primarily intended to determine the actual impact of drill site operations on the level of acoustic environment pollution. The monitoring enables to estimate the magnitude of the emitted noise and its duration. The measurements are then compared to maximum permitted levels under regulatory standards so as to establish the area of the impact and the degree of nuisance to the local communities. The tests were made according to methodology presented in Chapter 2.3. The scope of testing varied from one test site to another and was contingent on the type and schedule of works carried out by the Operators and on spatial characteristics of the test sites (clearance from the nearest residential buildings).

Survey teams first entered particular test sites at different stages of operations. At Wysin and Zawada test sites, they were able to establish the initial status of the acoustic environment prior to the commencement of works. At Lubocino, Stare Miasto, Syczyn and Gapowo test sites, noise tests started during site operations. The lack of baseline noise has not affected the subsequent interpretation, insofar as the noise generated during drill site operations was compared to the noise prevailing at idle time or on completion of works.

Lubocino Test Site

Since the survey was commenced at drilling preliminaries stage, the noise measurements made reflect the "as-found" status. The measurements were made at the drill site boundary and at the nearest residential buildings in the locality of Lubocino. The noise level measured at the outskirts of the village, in places most exposed to drill site noise, was found to be 37.9 dB (test point located 500 m NW of the site). It was equal to 50.6 dB before the buildings located 200 m N of the site. In immediate drill site proximity the noise was measured at 49.3 dB.

Subsequently, measurements have been made at drilling, fracturing and gas flow testing stages. The measurements were made concurrently at two points: near the drill site and at residential buildings located 500 m NW of the site. In the village, the noise had been usually much below the permitted level and only in 2 cases the permitted daytime level was exceeded (55.8 and 58.2 dB, i.e. 0.8 dB and 3.2 dB above the permitted level), while the permitted night-time level was exceeded in one case (46.6 dB, or 1.6 dB above the permitted level). Statistically, less than 2.5% of all readings exceeded the farmstead-permitted noise levels.

Noise data recorded throughout drilling, fracturing and gas flow testing operations enabled to track changes in the level of noise at the drill site and in the village. Usually, the changes with time were found to be highly concurrent in the two locations. Major noise changes at the drill site were followed by smaller noise changes in the village. The changes indicate that the drill site is the source of noise.

Noise tests were made on completion of works by the Operator. Measurements were made at 8 points and equivalent noise levels were calculated for each round. The obtained averaged value of 47.6 dB should be considered as the acoustic baseline for the test site.

The studies made at Lubocino test site have indicated that exploration does not involve any major nuisances to the population, in terms of compliance (with the requirements of Environment Minister's Ordinance of 14 June 2007 on the permitted noise levels in the environment, Journal of Laws No. 120, Item 826) and according to residents' opinion, as expressed at meetings with the survey team members.

Stare Miasto Test Site

Since test site operations were in progress, the baseline noise was measured on completion of Operator's work. The noise level was recorded as 53.1 dB. That value was assumed as the acoustic background for the period of drill site idleness.

The next round of measurements was made at hydraulic fracturing stage. The noise has been measured continuously for 3 days at the drill site and at a point located in the village (500 m away of the site). The permitted night-time and daytime noise levels have been slightly exceed in the village (by 0.7 dB and 1 db, respectively). However, by comparing the noise curves for the drill site and the village it was established that the source of a higher noise was located out of the drill site.

The results have clearly demonstrated that the noise emitted by the drill site had not contributed to the exceeding of the permitted levels and did not pose a risk to the quality of life of the residents.

Syczyn Test Site

Continuous noise level measurements were made simultaneously in two locations: at the drill site and at the nearest residential buildings located up to 150 m from the drill site. In addition, sequential measurements were made in 8 points around the site.

Measurements of reference, as required to establish the as-found status, were made at drilling preliminaries stage (drill site operations were in progress on the survey commencement day). Noise level measured at the site ingress gate was equal to 51.3 dB.

During hydraulic fracture stimulation, noise measurements were made in two stages. In the first stage, short-term noise measurements were made at points located in various directions at a distance ranging from 80 m to 220 m from the drill site. Simultaneously, the level of noise was measured at a permanent point located at the site ingress gate, where it was found to be relatively stable at 75 dB. The level of noise recorded in 8 points located out of the drill site ranged from 64.9 to 71 dB. At each point the noise has been measured for 5 minutes. At two points (separated by a residential building located at a distance of 80 m) the noise was in the order of 65 dB. This value should be adopted as the level of noise at the buildings.

To gain a more in-depth insight into the noise risk throughout the multi-stage fracturing operation, in stage two the noise was monitored continuously for a period 7 consecutive days. One monitoring point was located at the site ingress gate and the other at one of the nearest residential buildings, about 150 m away of the drill site. At the building, the daytime level of reference (55 dB) had been exceeded every day by: less than 5 dB (once), 5 to 10 dB (4 times) and by more than 10 dB (17 dB on one occasion). By comparing the curves of noise recorded at the drill site and at the building it was established that the exceedances were due to drill site operations. Nevertheless, these exceedances may be inflated, primarily by traffic noise at a road located near the drill site and by noise from day-to-day activities of the residents.

Wysin Test Site

Noise measurements made before the beginning of work by the Operators enabled to establish the initial status. Based on a short-time measurement, the baseline noise was found to be 52.4 dB.

Continuous noise measurements were made during drilling operations over a period of one week. The sound meter was installed at ingress gate, about 50 m away of the drilling rig. The value averaged for the entire period of measurement was 65 dB.

The test site is located in a farmland area, between the fields, at a local road, about 1 km away of residential buildings. Therefore, the range of elevated noise impact was established by measuring noise distribution around the test site, rather than noise measurements at the buildings. To this end, a second round of short-term (5 min) measurements of the equivalent noise level was delivered in 8 test points located circularly around the drill site at a radius of 200 m from the borehole being drilled. Simultaneously, another sound meter installed at the site ingress recorded the level of noise at the drill site. Noise levels measured at particular points ranged from 46.6 to 57.1 dB, and the average of 49.7 dB was by 5.3 dB lower than the permitted daytime level (55 dB).

Zawada Test Site

As the survey started before the beginning of project implementation, it was possible to measure the noise at the baseline determination stage. The measured noise level of 57.5 dB was distorted by unfavourable weather conditions (wind velocity was equal to 22.5 km/h at the time of measurement).

The next test round was performed during drilling operations. The level of noise was tested on a round-the-clock basis within the drill site perimeter. Equivalent sound level was equal to 61.9 dB for daytime and 64.9 dB for night-time. Moreover, short-time sound tests were made in the proximity of two nearest residential buildings located in different directions from the drill site. The distance between drill site and the houses was approx. 500 m and the sound level had been measured for 30 minutes. In front of the nearest house located east of drill site the equivalent sound level was equal to 43.8 dB. In the case of the nearest house located westward to the drill site the equivalent sound level was 50.6 dB. In view of these low levels of noise (despite the unfavourable weather conditions, at wind velocity in excess of 20 km/h), it was decided to discontinue noise monitoring in immediate proximity of residential buildings, considering the results of the tests made as a sufficient evidence that drilling operations at the drill site have no effect on the quality of life of the residents who occupy the nearest buildings. Simultaneously, noise levels had been measured at test points located around the drill site at a distance of approx. 300 m. Regardless of direction, the measured equivalent sound level ranged from 53.9 dB to 58.7 dB. The area surrounding the drill site is flat and free of terrain obstacles.

During hydraulic fracture stimulation the measurements were made in two stages. At the first stage, sound level has been recorded continuously at the drill site on a round-the-clock basis. The levels of noise was determined as 81.6 dB and 76.8 dB for daytime and night-time, respectively. During the test, acoustic screens have been installed south of pressure pumps with high output generator sets that were the main source of noise. On the eastern side, service containers were an acoustic barrier. Therefore, short-time noise measurements were made at a distance of approx. 60 m from the source of sound in different points (shield by the screen or exposed to the noise, so as to assess the effectiveness of the screens used). The noise was found to be noticeably lower (by 5–8 dB) behind the screens than in exposed places.

The second stage of measurements covered a single fracturing interval that lasted 50 minutes. The microphone was placed approx. 60 m away of the source of sound. Prior to and immediately after the interval the level of noise was equal to 60 dB. At fracturing operations, the level of noise was initially about 70 dB and then rose to 80 dB.

Test results have demonstrated that the drill site does not pose acoustic risks to the residents of the nearest houses, due to a sufficient drill site clearance from the buildings. Moreover, the Operator applied custom designed acoustic screens.

Gapowo Test Site

The first short-time noise measurement was made in Gapowo test site at a distance of approx. 40 m from the site fence at the time the drill site was idle. Sound level was found to be equal to 57.3 dB. On the same day the equivalent sound level of 51.5 dB was measured at the outskirts of Klukowa Huta village, at a distance of 600 m NW from the site.

Subsequently, measurements were made at drilling operations. The microphone was placed in the site perimeter near the security guard room. Equivalent sound level was found to be equal to 67.5 dB. The second round of noise measurements was delivered during drilling operations. The noise level was recorded simultaneously in the drill site perimeter and at the nearest residential building located about 350 m away of the drill site. The measured equivalent sound level was 62.4 dB. After analysing data from the microphone placed at the building (located in close proximity to the road) it has been established beyond any doubt that a peak on the noise recording curve is associated with each vehicle passing by.

In order to assess the effect of vehicular traffic on the equivalent sound level at the building, an additional test point was established at the same distance from the drill site, but far away of the road. The measured equivalent sound level of 51.4 dB was 11 dB lower than at the buildings near the road. This observation indicates that vehicular traffic may have a strong effect on the recorded levels of noise and sometimes (if not considered in a noise analysis) may lead to erroneous conclusions on drill site impact on the acoustic environment.

One more noise measurement was made upon completion of works. Night-time and daytime baseline sound level was determined over 4 consecutive days as 56.2 dB and 48.1 dB for daytime and night-time hours, respectively.

Conclusions

Based on the results of the tests made it has been concluded that noise nuisances did not occur at Lubocino, Stare Miasto, Wysin and Zawada test sites. This is substantiated by declarations of the local residents themselves whose opinion on the potential noise was sought. The distance to residential houses from the drill sites was 500 m or more. The Gapowo drill site did not generate any increase in noise level at neighbouring villages located at a distance of approx. 650 and 750 m, respectively. The case of an isolated farmstead located in immediate road proximity, 350 m away of the drill site, was examined in detail. It was concluded that a higher noise level was primarily due to vehicular traffic.

Syczyn was the only test site where noise standards have been exceeded as a result of drill site operations. The Syczyn site was located at the outskirts of a village. The nearest residential buildings were situated at a distance of several tens of meters from the site, more of them 150 m away and several other houses less than 500 m from the site. The standards for farmsteads (55 dB at night and 45 dB at daytime) have been exceeded on several occasions, both at night and during the day. The daytime exceedances were: 0–5 dB – once; 5–10 dB – once; 10–15 dB – 4 times; 15–20 dB – once; and at night-time: 0–5dB – once; and 5–10 dB – 3 times. The occupants of two nearest buildings were the most exposed.

The tests have clearly demonstrated that drill site operations have an effect on the acoustic environment in immediate drill site neighbourhood. Drill site clearance from residential areas is the key noise pollution limiting factor. As demonstrated at the Zawada test site, acoustic screens help reduce the level of noise. See Chapter 6.4 for a more in-depth discussion of these issues.

At the same time it is difficult to isolate the effect of vehicular traffic on the measured noise level when calculating the equivalent sound levels. Vehicular traffic must be taken into account, if buildings are located in immediate proximity of a road. This problem was encountered at Syczyn and Gapowo test sites.

4.2 Ambient air

Ambient air test were intended to estimate the size of emissions from shale gas exploration activities. The scope of testing, contingent on the specificity of works conducted at particular test sites, was designed so as to estimate emissions at different stages of Operators' work.

Lubocino Test Site

Since the investigations started when the Lubocino drill site was already in operation, it was impossible to establish the baseline of ambient air pollution. Air was sampled at several stages, while drilling, fracturing, at flowback fluid recovery, flowback fluid hauling, at gas flow testing and on completion of operations.

At borehole drilling stage, none of the measured parameters exceeded the value of reference. At fracturing stage, a significant increase in atmospheric concentrations of methane and C_2–C_{12} hydrocarbons was reported, but other parameters were within the permitted ranges. None of the determined parameters exceeded the value of reference at flowback fluid pumping from storage tanks to tank trucks.

Tests for suspended particles made at the as-found status, while drilling and during nitrogen treatment did not show any total particle concentrations above the values of reference, especially that Environment Minister's Ordinance of 26 January 2010 on the values of reference for certain airborne substances (Journal of Laws No. 16, Item 87) provides for permitted levels of particles having a diameter inferior to 10 µm, while total particles were measured without fractionation. The tests were delivered in the autumn/winter season, when rain and snowfalls prevent dusting.

Ambient air tests made on completion of Operator's activity did not reveal any elevated atmospheric concentrations of gaseous pollutants or total particles above the values of reference.

Higher concentrations of methane and other aliphatic hydrocarbons were recorded at fracturing, nitrogen treatment and gas flow testing stages, but on completion of these operations the concentrations fell to the baseline values. Ambient air tests made on completion of Operator's activity did not indicate any negative changes in the atmosphere.

Additional determinations of methane gas and C_2–C_{12} hydrocarbons were made directly above the flowback fluid storage tanks at the stages of flowback recovery and gas flow testing. Air was sampled

directly above the fluid in a gas-buster tank (an open tank enabling turbulent flow and degassing of liquids) when, for process reasons (too small gas volumes in the fluid), the separators were not connected to the fluid recovery line. A surge in atmospheric concentrations of C_2–C_{12} aliphatic hydrocarbons and methane occurred. Top concentrations were 1 400 000 µg/m^3 and 653 660 µg/m^3 for C_2–C_{12} aliphatic hydrocarbons and methane, respectively. Simultaneously, a sample was collected at a distance of 50 m from the tank. Methane concentration fell to 1 410 µg/m^3 and that of C_2–C_{12} hydrocarbons to 24 000 µg/m^3, i.e. the concentration were decreasing quickly with distance and did not pose a risk of explosion[9].

The tests of the above samples revealed an emission of volatile hydrocarbons to the atmosphere that occurs at least in the initial phase of flowback fluid recovery from the well. Similarly, at the gas lift phase, when nitrogen or other non-flammable gas is the main gaseous constituent of the flowback fluid, despite the application of separators methane concentration at the flare is too low to support the flame and all the gas is vented to the atmosphere. Unfortunately, the measurements of atmospheric gas concentrations did not allow for estimation of the total gas loads emitted to the atmosphere.

Stare Miasto Test Site

Since the investigations started when the Stare Miasto drill site was already in operation, it was impossible to establish the baseline of ambient air pollution. Therefore, measurements were made on completion of Operator's activity and the results have been compared with the measurements made at hydraulic fracture stimulation stage. A significant increase in the concentration of C_2–C_{12} hydrocarbons and almost two-fold increase in sulphur dioxide concentration, exceeding the value of reference, was detected at the stage of hydraulic fracture stimulation. Significant changes in the remaining parameters were not detected, comparing to the measurements made on completion of drill site operations.

Syczyn Test Site

Ambient air samples collected at the as-found status were tested for selected indices of potential pollution. Concentrations of all indices were below the value of reference. Total suspended particles were below the limit of detection (200 µg/m^3).

At fracturing stage, only sulphur dioxide concentrations exceeded the value of reference. The determined sulphur dioxide concentration of 386 mg/m^3 was slightly above the value permitted for 1 hour (350 mg/m^3) and fell to 146.2 mg/m^3 after two hours. Other pollutants, including total particles, have not exceeded the value of reference, although atmospheric concentrations of C_2–C_{12} hydrocarbons and volatile organic compounds increased significantly in the final hours of fracturing operations.

Wysin Test Site

The initial status was established prior to the commencement of any works by the Operator. No exceedances were found in the tested samples.

Two air samples were collected during drilling operations. Benzene was not detected in any of them, while concentrations of sulphur dioxide and nitrogen oxides were very low, 8 to 20 fold lower that the value of reference. The samples were also tested for methane and total volatile organic compounds (VOC). The concentrations of these substances were similar at baseline status and at well drilling stage. In the first sample, the concentration of C_2–C_{12} hydrocarbons (3920 µg/m^3) was slightly above the value of reference (3000 µg/m^3). In the second sample, collected an hour later, C_2–C_{12} concentration fell to 3000 µg/m^3. The tests for total particles did not reveal any exceedance of the value of reference.

Zawada Test Site

Tests for suspended particles were made and air samples collected before the beginning of drilling operations. At drilling stage, air samples were collected but the tests for air particles were cancelled due to inclement weather – a strong wind, precipitations and snow cover. Tests for suspended particles were made and air samples collected at the stage of fracturing.

[9] Due to the sampling location, the tests of gas collected over the gas-buster tank are not included in the Table 4.

During the as-found status investigations, only the concentration of C_2–C_{12} hydrocarbons (3500 µg/m^3) was found to be higher than the value of reference. Quite likely, the tests detected traces left by machines that were building the embankment (ongoing drill site construction operations). Concentrations of the remaining pollutants were much below the value of reference. Total suspended particles were below the limit of detection (200 µg/m^3).

All concentrations of air pollutants were below the value of reference at hydraulic fracture stimulation stage.

Gapowo Test Site

Ambient air samples were collected for chemical tests and suspended particle determinations before the well was spud in. Concentration of all indices tested were below the value of reference. In the case of non-standard values (methane, total volatile organic compounds (VOC)), the results are typical for background levels. At the as-found status, total suspended particles were below the detection limit of the applied method (40 µg/m^3).

At drilling stage, samples have been collected near the potential source of pollution. The results show that none of the measured parameters has exceeded the value of reference. Concentration of C_2–C_{12} hydrocarbons was close to the value of reference (2260 µg/m^3 and 2960 µg/m^3) but never exceeded it and was similar to the value determined for the as-found status (2655 µg/m^3). Also methane and total volatile organic compounds (VOC) concentrations were similar to those established for the as-found status. Worth of noting is an increase in sulphur dioxide concentration to 133 µg/m^3, probably due to the operation of combustion engines located near the machines. This concentration still represents less than 40% of the value of reference and does not pose any risk. Total suspended particles were below the detection limit of the applied method (40 µg/m^3).

Subsequent test rounds were delivered at the stage of fracturing and a month later during nitrogen treatment operations. In both rounds samples were collected leeward just behind the drill site fence. The results indicate that sulphur dioxide, nitrogen oxides, benzene and BTEX concentrations are several times lower than respective values of reference, although they are slightly higher than in previous tests. On the other hand, the concentrations of methane, C_2–C_{12} hydrocarbons and VOC were several times higher. The atmospheric concentration of C_2–C_{12} hydrocarbons (8544 µg/m^3) was almost three fold higher than the value of reference at the stage of fracturing and over two fold higher (6540 µg/m^3) during nitrogen treatment operations. Throughout all stages, these were the only cases in which the value of reference has been exceeded. Prior to the beginning of the process, in the as-found status, the concentration of hydrocarbons (2655 µg/m^3) almost equalled the value of reference (3000 µg/m^3).

At hydraulic fracturing stage, total suspended particles were determined at 60 µg/m^3, much below the value of reference. Following the test, a cloud of dust released from a tank truck being unloaded was observed. Therefore, an additional test of dust concentration was made in immediate proximity of the unloaded truck. The measured concentration was equal to 2560 µg/m^3. This result is not associated with fracturing operations themselves, but with related proppant handling operations.

On completion of drill site operations, an air sample was collected on 23 October 2014 and tested for organic compounds: methane, hydrocarbons, VOC, benzene and BTEX. The conclusion from the tests made is that the on completion of operations the state of air was similar to the as-found status and the concentration of the tested substances have not exceed the values of reference.

Conclusions

At all test sites the values of reference for NO_x, benzene and BTEX have not been exceeded. Exceedances were most frequently reported for C_2–C_{12} hydrocarbons (above 3000 µg/m^3). They occurred at four test sites (Lubocino, Wysin, Zawada, Gapowo), and at two other the concentrations were close to the value of reference. Sulphur dioxide concentrations were above the value of reference at two sites (Stare Miasto and Syczyn). Top concentrations of the tested indices are presented in the Table 4.1.

Notwithstanding the results, the effect of hydrocarbon emissions to the atmosphere occurs at fracturing fluid recovery from the well and the magnitude of these emissions can be only estimated from the measured momentary concentrations that are highly variable with time. The Operators are recommended to minimize the emissions by activating the separators as early as possible at flowback fluid recovery operations and by applying available afterburner techniques, if gas concentrations are too low for self-ignition.

Table 4.1. Top concentrations of indices tested at particular test sites

Indices / Test site	SO_2 [µg/m³]	NO_x [µg/m³]	Methane [µg/m³]	C_2–C_{12} hydrocarbons [µg/m³]	VOC [µg/m³]	Benzene [µg/m³]	BTEX [µg/m³]
Value of reference averaged for 1 h*	350	200	nn	3000	nn	30	850
averaged for 1 year	20	40	nn	1000	nn	5	63
*Permitted level** averaged for 1 h*	350	nn	nn	nn	nn	nn	nn
averaged for 1 year	20	30	nn	nn	nn	5	nn
Lubocino	169 (p)	109 (p)	10108 (p)	7620 (p)	11177 (p)	6.0	23.5 (p)
Stare Miasto	815 (s)	105 (s)	1300 (s)	2900 (s)	5500 (s)	< 1	485 (s)
Syczyn	386 (s)	88,7 (z)	1300 (z)	2800 (z)	15400 (s)	< 1	120 (s)
Wysin	18 (w)	24 (w)	1000 (z)	3920 (w)	6600 (z)	< 1	635 (w)
Zawada	119 (s)	62 (s)	1400 (z)	3500 (z)	6500(z)	< 1	230 (s)
Gapowo	133 (w)	47 (w)	3470 (s)	8544 (s)	32714 (a)	3.2 (s)	33 (s)

The value of reference exceeded

* *values of reference according to Environment Minister's Ordinance of 26 January 2010 on the values of references for certain airborne substances (2010 Journal of Laws No. 16, Item);*

** *permitted levels according to Environment Minister's Ordinance of 20 August 2012 on the permitted levels of certain airborne substances (2012 Journal of Laws, Item 1031);*

The stage of operations at sampling is indicated in parentheses ( ):

z – as found or baseline status, w – drilling, s – fracturing, p – flowback fluid recovery.

The tests of total suspended particles did not reveal any direct increase in dust concentration from drilling, fracturing or gas-flow testing operations. On the other hand, a very high increase in total suspended particles concentration has occurred at one test site at handling operations (proppant transfer from a tank truck to the storage tanks). Unloading a single tank truck took only about 1 hour and the range of impact was small (the cloud of dust quickly settled on the ground).

Dusting may also be related to the transport on the local dirt roads of access to the drill site. In most cases, the Operators paved the dirt access roads with concrete slabs and aggregate. The additional effect was reduced dusting. At Zawada test site, the Operator also sprinkled the road.

A majority of air pollution risks spontaneously disappear on completion of works as a result of air exchange. On clearing the ground surface from pollution sources, atmospheric pollutants are dissipated in open space.

4.3 The soil

The impact on the soil from drilling and well stimulation operations derives from direct loads on the soil, mechanically-induced changes in the profile as a result of site leveling and topsoil removal, but may also involve contamination with substances used on the drill site. In the event of upward gas migration from geologic formations via privileged pathways, such as along the well casing walls,

higher gas concentrations should be expected in the soil gas. As soon as the gas passes into the atmosphere, these concentrations fall to undetectable levels. Therefore, on site tests focused on both mechanical properties and soil chemistry, including that of soil gas.

Lubocino Test Site

The as-found status of the Lubocino site was established at the first testing round when drilling operations and hydraulic fracturing stimulation of Lubocino-1 well were underway. The drill site has not been abandoned by the final day of this project. Accordingly, it was decided to refrain from soil studies at Lubocino test site (soil pollution, alteration of properties due to soil piling). The analysis of drill site impact on the soil is based on soil gas tests for hydrocarbons and radon gas.

The tests of soil gas sampled at two test rounds showed elevated concentrations of hydrocarbons in the proximity of the Lubocino-1 well. The range of higher concentrations (comparing to other sampling points) was different than that established before fracturing operations: the concentrations were lower in immediate Lubocino-1 well neighbourhood, but increased northwest and northeast of the well. It is difficult to explain the reasons behind these higher concentrations and changes in the affected zone range.

Component ratios and isotopic tests indicate that recent geochemical processes are influencing the soil gas composition at Lubocino test site, with a small contribution of migration from the reservoir in the near-well zone and traces of anthropogenic pollution from the ground surface.

Soil gas test for radon (222Rn) have not indicated any effects of fracturing operations on the content of this radionuclide. The reported concentrations are characteristic of the local geology.

According to the tests made during and on completion of drilling and multi-stage hydraulic fracture stimulation of Lubocino-2H well, these process did not represent a serious burden to the environment. By the time this study was completed, no serious changes in the natural environment that could be attributed to these operations had been detected. The only exception are elevated soil gas concentrations of hydrocarbon found within the drill site at both as-found status and on completion of work at Lubocino-2H well, but the reasons thereof have not been unequivocally established.

Stare Miasto Test Site

Due to Operator's schedule of works and the term of the project, the baseline status (prior to the commencement of any operations) was not established. Moreover, the survey team was unable to determine the environmental impact from vertical well drilling operations. The as-found status was established immediately before the beginning of hydraulic fracture stimulation.

Concentrations of gaseous geochemical indices in soil gas samples are similar to environmental background values. Anomalous carbon dioxide concentrations in soil gas samples are the only exception, but they should be attributed to recent geochemical processes. Only traces of other analysed gaseous geochemical indices were found in the samples.

A low concentration of methane prevented an isotopic analysis of that gas, as required for the determination of its origin. The topsoil gas methane is likely to be of mixed origin. Based on atmogeochemical tests it was established that hydraulic fracture stimulation had no effect on the soil gas composition in the drill site area.

Variations in radon (^{222}Rn) concentrations in the soil gas follow typical patterns. A comparative study of two test rounds showed that arithmetic mean rose from 10.2 to 18.4 kBq/m^3, while the upper limit of the concentration range fell from 48.7 to 42.9 kBq/m^3.

Hydraulic fracture stimulation was delivered according to the technical programme and no unforeseen events that could have a direct effect on the environment, other than emergency flowback fluid spill from the flare that lasted for a few minutes, were not reported. Potential consequences of that emergency event have been investigated under a modified testing programme (a supplementary test round).

The effected tests have not unequivocally ascertained the impact of flowback fluid spill through the flare on the soil environment. The spill covered a small area in eastern and southern parts of the drill site. A comparison of hydrocarbon content in the samples collected in 2012 and 2014 (total hydrocarbons ranged from 10.915 to 66.478 mg/kg dw and from 100.581 to 198.296 mg/kg dw, respectively) testifies to higher concentrations of hydrocarbons on completion of site reclamation operations. However, it is impossible to state clearly whether these concentrations stem from drill site operations or, for example, from the process of spreading the topsoil piled in the embankments and site ploughing. The compounds with higher

concentrations belong mainly to the mineral oil groups that are used in geological works and agricultural machinery alike. Since the concentrations do not exceed threshold values for the B-class soil at a depth of more than 30 cm (according to Environment Minister's Ordinance of 9 September 2002 on soil quality standards and ground quality standards), that are expected to disappear from the soil soon as a result of natural biodegradation stimulated by aeration and farming procedures, such as ploughing and fertilisation.

On the other hand, a low content of humus and humic acids (0.60 Kh) at the southern part of the drill site is worth of noting. This may attest to mechanical soil degradation at the drill site development stage.

A comparison of sample tests from the two rounds of measurements revealed that drill site operations have not contributed to the deterioration of soil quality at the site of Operator's activities. A much higher content of phosphorus and potassium in the samples arises from the use of fertilizers by the field owner.

Tests made with high resolution terrestrial laser scanning (LiDAR) did not reveal any direct effect of hydraulic fracture stimulation on the activation of mass movements on the slope of a sand pit located east of the site.

According to subsoil compaction studies made within the drill site perimeter and in areas adjacent thereto after a month of site abandonment and reclamation, the soil profile compaction did not occur, i.e. farming conditions did not deteriorate as a result of soil compaction from the loads of drilling and services facilities.

Syczyn Test Site

A comparison of methane concentrations established in four test rounds (Tables 2.5 and 2.7) reveals that, some fluctuations apart, they are very high and tend to increase with time. In the set of 2012 data (25 test points), arithmetic mean is equal to 11553.8 ppm, the median is 4.0 ppm, and the maximum value is equal to 225000.0 ppm. In the 2014 data set (53 test points), these value were as follows: arithmetic mean – 21044.2 ppm, median – 8.4 ppm, maximum concentration – 354056.0 ppm.

Higher concentrations occur in northern part of the tested area. Higher methane concentrations were not found at any of the test rounds near the farmsteads and residential buildings located westward of the drill site. Only two of all test points with high methane concentrations are located out of the area covered with concrete slabs. In other high methane points the soil gas is isolated from the atmosphere by the aforementioned concrete slabs. By isolating the subsurface soil from the atmosphere, the "screen" establishes favourable conditions for microbial fermentation at limited availability of oxygen and hinders soil gas exchange with the atmosphere.

Total C_2–C_5 alkene concentrations recorded at four test rounds did not show any clear pattern of changes with time. This statement is substantiated by the mean (46.8 ppm in 2012 and 42.5 ppm in 2014) and median values (0.042 ppm in 2012 and 0.036 ppm in 2014). Like in the case of methane, higher concentrations tend to concentrate in northern part of the tested area. The methane to alkanes ratio ($C_1/\Sigma(C_2–C_5)$ ratio > 1000) indicates a recent origin of methane concentrations.

Higher methane concentrations were not found at test points located along the horizontal leg profile at any of the test rounds, save for one point in which methane concentration was equal to 570 ppm in October 2013. A lack of higher methane homologues in that sample suggests its recent origin.

A comparison of carbon dioxide concentrations reported from four test rounds reveals highly variable figures. The highest carbon dioxide concentration (19.67 vol.%) was measured in October 2013. Also the highest measures of the carbon dioxide concentration data set were reported from that test round: mean concentration equal to 4.18 vol.% (in other rounds it ranged from 1.67 to 3.13 vol.%) and the median of 2.17 vol.% (from 0.57 to 1.19 vol.% in other test rounds).

Outstanding carbon dioxide concentrations occur in northern part of the tested area and follow the pattern of high methane concentrations. This indicates that higher carbon dioxide concentrations can be attributed to recent biochemical processes.

Concentrations of carbon dioxide, hydrogen and methane displayed the highest variability throughout the test period (from October 2012 to July 2014). These results suggest a variable rate of recent temperature- and soil moisture-dependent biochemical processes (Buraczewski, 1989; Waleńczak, 1987). Moreover, by isolating the subsurface soil from the atmosphere, the "screen" establishes favourable conditions for microbial fermentation at limited availability of oxygen and hinders soil gas exchange with the atmosphere.

Worth of noting is a surge in carbon dioxide concentrations reported from the third testing stage (October 2013). This may be a result of more intense recent biochemical processes in the soil following higher summer temperatures. However, hydrogen concentrations do not support this hypothesis. Therefore, it is reasonable to suspect that higher soil gas concentrations of carbon dioxide may include a deeper component, i.e. associated with the presence of coal beds (Bogdanka Coal Mine) and/or disruption of beds with natural carbon dioxide accumulations (e.g. Carboniferous formations) while drilling.

The results of isotopic tests (made at the second and the third stage) indicate that methane measured in the soil gas is mainly a product of microbial fermentation of simple organic compounds. Microbial methane contains a small admixture of thermogenic gas. This may be due to the migration of gas from coal deposits. The thermogenic gas is certainly not associated with Silurian rocks (the exploration target at Syczyn).

Measurements of methane and carbon dioxide emissions made in 2014 (one year after fracturing operations) showed that gas emissions are low and do not pose a risk to the environment. At the test point where during sampling operations in 2014 (see Table 2.5 for the sampling schedule) the highest methane concentrations were found (354000.0 ppm), gas concentration in the static chamber increased from 3.2 ppm to 10 ppm, while carbon dioxide concentration fell from 0.19 vol.% to 0.14 vol.%. A positive methane emission value of 16.1 [$mg*m^{-2}*d^{-1}$] was recorded.

In two other test points methane concentrations tended to decrease: from 2.6 to 2.1 ppm and from 2.3 to 2.1 ppm. The calculated methane emissions turned out to be negative. On the other hand, carbon dioxide concentrations slightly increased from 0.13 vol% to 0.19 vol.% in one test point, but felled from 0.2 vol.% to 0.16 vol.% in other point.

Falling methane concentrations at increasing carbon dioxide contents can be attributed to microbial methane oxidation to carbon dioxide (Buraczewski, 1989; Waleńczak, 1987; Le Mer, Roger, 2001; Zhang, Chen, 1985; Whiticar et al., 1986). Accordingly, a negative emission means that methane flowing out of the soil is decomposed by bacteria (Etiope, Klusman, 2002).

Despite the high concentrations of methane and carbon dioxide in the soil gas, their emissions, as measured on the test site, are relatively small. Similar studies carried out, for example, in the Wałbrzych and Nowa Ruda Basin (Korus et al., 2002; Dzieniewicz et al., 2006; Sechman et al., 2006) have demonstrated that methane and carbon dioxide inputs to the atmosphere do not pose a risk to the environment and public safety.

The tests for radon (^{222}Rn) concentrations in the soil gas were delivered on a comparative basis in two rounds: the first round before and the second after hydraulic fracture stimulation. The arithmetic mean of radon (^{222}Rn) concentration in the soil gas was slightly higher in the second round (an increase from 10.1 to 11.3 kBq/m^3). These changes, however, reflect the natural variability in near-surface rocks and radon (^{222}Rn) concentrations are characteristic of the investigated region.

Wysin Test Site

Only traces of total C_2–C_5 alkanes and total C_2–C_4 alkenes (on average 0.2 ppm and 0.008 ppm, respectively) were detected in soil gas samples collected at the Wysin test site. Hydrogen was virtually absent and a higher concentration of carbon dioxide was found only in one sample (approx. 3.3 vol.%, at average equal to 0.8 vol.%). The measured contents naturally occur in subsurface soils.

Abnormal methane concentrations found immediately above the fen are attributed to recent biochemical processes. A higher concentration of methane at the absence of its heavier homologues indicates that methane derives from (depending on actual conditions) methane fermentation, CO2 reduction or from microbial activity.

Radon (^{222}Rn) concentrations in the soil gas, as measured in 16 test points, ranged from 3.8 kBq/m^3 to 41 kBq/m^3 (10.5 kBq/m^3 on average).

The results of subsurface geochemical tests show that the measured concentrations of hydrocarbons are on a trace level. Their distribution patterns follow the natural geochemical background of the investigated region. Also radon (^{222}Rn) concentrations in the soil gas are typical for the analysed area.

The tests for radon (^{222}Rn) and methane concentrations made in the PEHD sheet lined drill site area did not reveal any gas accumulation in the soil gas (average concentration was equal to 12.0 kBq/m^3). The reported radon (^{222}Rn) concentrations in the soil gas are typical for the investigated region. Methane concentrations in the soil gas were similar to those reported from the first test round (arithmetic mean was equal to 2.9 ppm and 2.95 ppm in the first and second round, respectively).

At the baseline status determination stage, soil samples were tested for organic indices of pollution. The results show a slight exceedance of the maximum permitted concentrations (MPC) in soils designated as farmland (under Environment Minister's Ordinance of 9 September 2002 on soil quality standards and ground quality standards). The maximum permitted concentration of gasoline was exceeded in one topsoil sample (1.174 mg/kg, at MPC equal to 1 mg/kg), and the maximum permitted concentration of total aromatic hydrocarbons was exceeded in all samples (0.146–0.391 mg/kg at MPC equal to 0.1 mg/kg).

The soil was tested for compaction in order to determine any potential effect of the subsequent (following well abandonment) engineering and heavy equipment operations and high topsoil piles on the subsoil compaction. The first test was delivered prior to drill site development. In consultation with the Contracting Authority, it was decided to refrain from the second test round. An impoverished plant cover in the embankment area was reported from drill site inspection made on site clearing. This may indicate a change in soil properties (structure) from the loads of piled embankments.

Tests made with high resolution terrestrial laser scanning (LiDAR) were intended to identify any potential impact from drill site operations on changes in the terrain morphology. To this end, a 3D survey of the site was delivered prior to drill site development. The second round of the survey, intended to identify potential terrain deformations, was cancelled in consultation with the Contracting Authority. Therefore, a differential DTM-based study on potential terrain deformations was not effected.

Zawada Test Site

The survey of the Zawada test site started before the drill site development by the Operator, including in particular topsoil piling. This enabled soil sampling, as required for the determination of the initial environmental status.

Soil tests for compaction were made at the first stage of operations (baseline status, August 2012) so as to obtain comparative data for subsequent studies on potential subsoil compaction by engineering operations, high topsoil piling and operation of heavy mobile equipment.

Soil samples collected at the baseline determination stage were tested for pollution indices. The tests showed slight exceedances of maximum permitted concentrations (MPC) in farmland soils (under Environment Minister's Ordinance of 9 September 2002 on soil quality standards and ground quality standards) for gasoline in one sample (1.195 mg/kg at MPC equal to 1 mg/kg) and mineral oil in one sample (53.593 mg/kg at MPC equal to 50 mg/kg), as well as for total aromatic hydrocarbons in all samples (0.209-0.3980 at MPC equal to 0.1 mg/kg).

A comparative study on the site impact was not performed, since as of the final day of this project the drill site has not been abandoned and the sealing sheet removed.

Soil gas tests have been carried out in several rounds (Tables 2.5 and 2.7). As a general rule, methane concentrations determined in July 2014 are higher than in previous test rounds. The top concentration determined in July 2014 is higher by an order of magnitude than that of October 2013 and by four orders of magnitude than the maximum value found at the initial status. The increase is also reflected by the arithmetic mean values, which amounted to 1.2 ppm, 335.3 ppm and 545.5 ppm for test data sets of 2012, 2013 and 2014, respectively.

In both rounds (of October 2013 and July 2014), test points with outstanding (elevated) methane concentrations were located in northern and north eastern part of the test site. On the other hand, methane concentrations at points located 20–40 m away of the drill site varied from approx. 1 ppm to 2.8 ppm, i.e. were in the range of natural background of metane in soil gas (Tedesco, 1995).

An analysis of the measured concentrations by geochemical indices showed that carbon dioxide, hydrogen and methane concentrations were the most variable with time. In 2014, carbon dioxide concentrations fell, whilst those of hydrogen and methane were up. The results suggest a change in the intensity of ongoing biochemical processes, most probably under the influence of soil temperature and humidity.

An analysis of stable carbon isotopes in the methane, ethane, butanes, pentanes and carbon dioxide, as well as of stable hydrogen isotopes in the methane of natural gas (reservoir gas) from Silurian formations and of C_{HC} and CDMI indexes revealed that the tested topsoil gas is of microbial origin (produced by microbial fermentation, i.e. by living organisms). Carbon dioxide contained in the topsoil gas seems to be of thermogenic origin. However, the isotopic shift towards thermogenic gas may arise from secondary oxidation of microbial methane in subsurface topsoil zone. The topsoil gas is certainly not genetically akin to the Silurian gas.

Emissions were tested using the modified static chamber method in 2014 (one year after fracturing operations) at test points that have been selected considering outstanding high concentrations of methane and carbon dioxide in soil gas samples.

The measured positive emissions of methane and carbon dioxide are relatively small. Similar studies carried out in the Wałbrzych and Nowa Ruda Basin (Korus et al., 2002; Dzieniewicz et al., 2006; Sechman et al., 2006) have demonstrated that methane and carbon dioxide inputs to the atmosphere do not pose a risk to the environment. Methane and carbon dioxide inputs from deep strata are small, while any anomalous gas concentrations that occur in the soil gas should be considered as products of recent biochemical processes. This was corroborated by the tests of molecular and isotopic composition.

The tests for radon (^{222}Rn) concentrations in the soil gas were delivered on a comparative basis in two rounds: the first round before and the second after hydraulic fracture stimulation. The arithmetic mean of radon (^{222}Rn) concentration in the soil gas was slightly higher in the second round (an increase from 12.0 to 12.5 kBq/m^3), while the upper limit of concentrations was slightly lower (35.0 against 33.7 kBq/m^3). The reported concentrations of radon (^{222}Rn) in soil gas should be considered as characteristic of the investigated area and their variability reflects natural changes that occur in the topsoil.

Łebień Test Site

From among all the gas constituents tested after two years of hydraulic fracture stimulation, higher concentrations were found for methane (max. 12180.0 ppm) and carbon dioxide (max. 13.3 vol.%), at average contents of methane and CO_2 equal to 856.9 ppm and 4.4 vol%, respectively. Molecular gas composition ratios in these samples suggest they are of a natural biological origin. Higher methane homologues detected in some of the samples indicate migration of hydrocarbons from deep geological formations. However, the reported concentrations are of a trace level and their occurrence in the topsoil is a result of microseepage from deep accumulations.

Elevated methane concentrations, found mainly near the wellhead in southern and eastern parts of the tested area, are generally accompanied by higher carbon dioxide concentrations. Similar distribution patterns of methane and carbon dioxide confirm the suggested recent biological origin of these gases.

Two soil gas samples collected at Łebień test site in December 2013 were tested for stable carbon isotopes in methane and carbon dioxide, as well as for stable hydrogen isotopes in methane gas. The results show that abnormally high methane and carbon dioxide concentrations in the topsoil derive from microbial fermentation (i.e. are produced by the action of microorganisms).

Soil tests made in selected points, near a drilled water well located within the site perimeter and at a nearby process fluid handling site where the fluids have been transferred from an earthen tank to tank trucks, were intended to check for potential process fluid spills causing soil contamination and migration of contaminants to the aquifer.

Physicochemical indexes determined in the soil samples collected near the drilled water well and the process fluid handling location were compared to the threshold values (MPC) for B-Class soils (farmland soils, under Environment Minister's Ordinance of 9 September 2002 on soil quality standards and ground quality standards, Journal of Laws No. 165, Item 1359). None of the parameters regulated by the law (barium Ba, C_6–C_{12} gasolines, C_{12}–C_{35} mineral oils) exceeded the MPC (top concentrations were 58 mg/kg, <10 mg/kg and <0.5 mg/kg for barium, C_6–C_{12} gasolines and mineral oil, respectively. The concentration of Cl, Br and Ca (i.e. the elements with highly elevated groundwater concentrations – see Chapter 4.4.1) are within ranges that are typical for the soil and ground (maximum concentrations were equal to 108.8 mg/kg, 5.2 mg/kg and 8135.0 mg/kg, for Cl, Br and Ca, respectively. Worth of noting are high concentrations of Fe (on average 10644.6 mg/kg), Na (on average 226.4 mg/kg) and K (on average 1331.0 mg/kg) which depend on sampling depth and the type of soil.

Gapowo Test Site

Surface geochemical surveys were carried out in the Gapowo test site region in December 2013 (as-found status) and in September 2014 (following hydraulic fracture stimulation). At each stage, topsoil samples were collected at test points located along the site fence, as the entire drill site area was lined with geomembrane.

At both test rounds only traces of hydrocarbon components (methane, total C_2–C_5 alkanes, total C_2–C_4 alkenes) were detected in soil gas samples. In the case of hydrocarbon components, were slightly lower in 2014 comparing with the 2013 level.

The increase in carbon dioxide concentrations reported in 2014 is unrelated to other geochemical indices and should be attributed to seasonal variations. Carbon dioxide concentrations tend to increase after warm seasons and to fall in cold seasons of the year (Farmer, 1964; Risk et al., 2002).

The measured concentrations of hydrocarbons and the variability thereof occur naturally in the soil environment. They do not exceed the background established for oil- and gas-bearing regions (Sechman et al., 2011). The increase in carbon dioxide concentrations, as reported in 2014 comparing to 2013 tests, is part of seasonal variations.

Conclusions

Interrelations between constituents and isotopic tests indicate that soil gas composition and variability is primarily controlled by recent biochemical processes.

Test results indicate that the concrete slab-covered geomembrane lining acts as a "screen" which, by isolating the topsoil from the atmosphere, establishes conditions that are favourable for microbial fermentation (Whiticar et al., 1986; Buraczewski, 1989; Le Mer, Roger, 2001; Kunicki – Goldfinger, 1994) in an oxygen-deficient environment, at limited exchange of soil gas with the atmosphere.

Radon (^{222}Rn) concentrations in the soil gas at the tested sites derive from radon generation by radioactive decay of uranium contained in the subsurface Quaternary Scandinavian rock material and are not associated in any way with drill site operations. The reported variability of soil gas radon (^{222}Rn) concentrations is a natural phenomenon. As a general rule, concentrations of that gas are highly variable in the soil and are controlled by several factors, including primarily atmospheric conditions and highly variable lithology and thickness of rock strata in the surveyed area. In anthropologically unchanged Quaternary soils radon concentrations range from 0.1 to 135.5 kBq/m^3 (Wołkowicz, Karpińska, Stec, 2007).

Considering its short half-life (3.8 days), it is estimated that radon (^{222}Rn) can pass to the atmosphere from a maximum depth of 200 m under favourable conditions, i.e. at high permeability of the rock medium and an elevated uranium content. Exceptionally, radon (^{222}Rn) may migrate from deeper rocks along tectonic dislocations or gas well casing walls, but this was not the case in this survey.

4.4 Surface and ground waters

The determination of the actual effects of drill site operations on the surface and ground waters (quantitative and chemical status) was the key objective of monitoring studies delivered at particular test sites. The tests, made according to methodology presented in Chapter 2.6, were preceded by an assessment of potential impacts on the surface and ground waters. This determined both programme and frequency of testing. The full testing cycle served as a basis for development of recommendations for the delivery of long-term monitoring (Fig. 4.1).

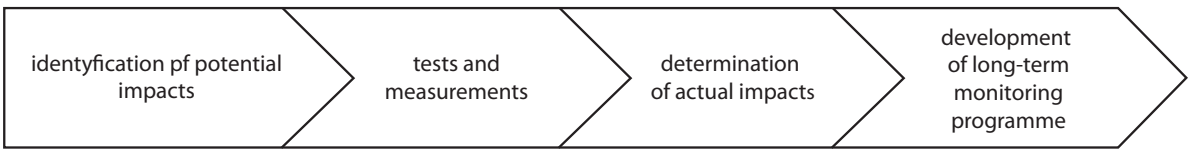


Fig. 4.1. Overall programme of testing stages.

Testing programme varied from one test site to another, considering both scope and schedule of works delivered by concession operators, site accessibility, as well as hydrogeological and environmental conditions in the test site area (Table 4.2). Hydrogeological conditions, including the profile of natural resistant to pollution and available water resources, are presented in Chapter 3.4 of this Report.

Table 4.2. Level of reference and the number of test rounds in particular test sites

Test site	Lubocino	Stare Miasto	Syczyn	Wysin	Zawada	Łebień	Gapowo
Level of reference (baseline)	as-found status	as-found status	as-found status	initial status	initial status	as-found status (July 2011)	as-found status
Fracture stimulation	yes (horizon-tal)	yes (horizon-tal)	yes (horizon-tal)	no	yes (vertical)	yes (horizontal)	yes (horizontal)
Site reclamation	no	yes	no	yes	no	partly	no
No. of test rounds	3	4	5	1	4	3	2

Considering the local conditions (Table 4.3), the following interim targets have been set when planning the survey at particular test sites with a view in assessing the actual impact of drill site operations on the aquatic environment in the area of works:

- the determination of the impact on the topmost aquifer (drill site operations performed on the ground surface),
- the determination of the impact on the main commercial aquifer – the main source of potable water supply to the population,
- the determination of the impact on the impact on deep aquifers (secondary commercial aquifers),
- the determination of the impact on the Main Groundwater Reservoirs,
- the determination of the impact on the quality of the surface waters,
- the determination of the impact on the quantitative status of surface and ground waters (% of water reserves used),
- the identification of the potential risk of reservoir and process fluid penetration to the aquifers (from the fracture stimulated well interval).

4.4.1 The extent of impact on the quality of surface and ground waters

The extent of impact from drill site operations on water chemistry (quality) has been determined on the basis of the tests made in all aquifers present in particular test site areas (Table 4.3). The number and schedule of surface and ground water test rounds in particular test sites are presented in the Methodology Chapter (Table 2.9).

Table 4.3. Aquifers in test site areas by number and type

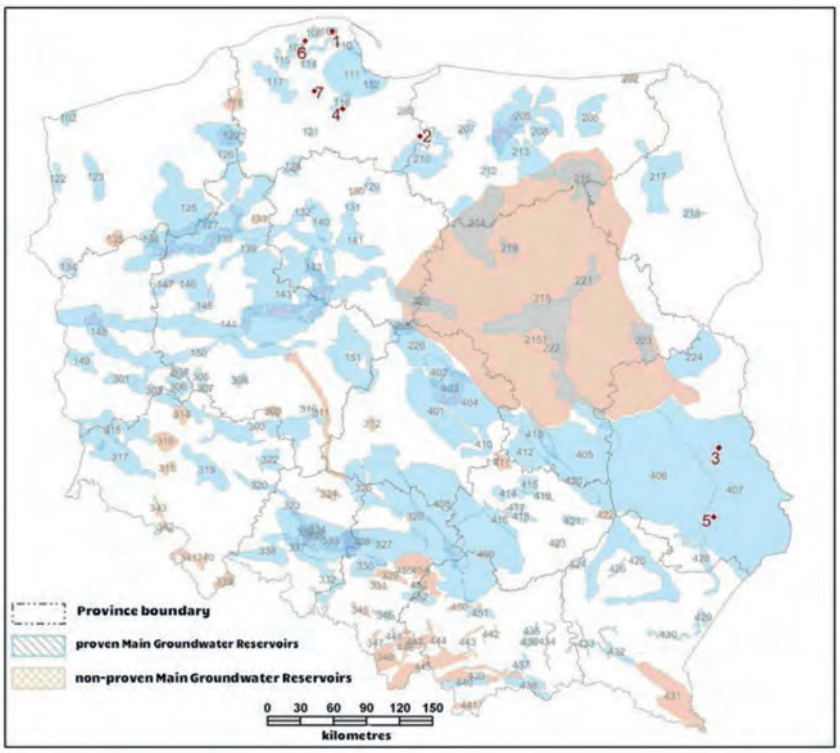
Test site	Perched aquifers	TA	MCA	CA	MGR (age of MGR medium)
1	2	3	4	5	6
Lubocino	2 aquifers	TA = MCA (Quaternary)		Oligocene	1 km from MGR 109 (Quaternary)
Stare Miasto	none	TA (Quaternary)	MCA (Quaternary)	Quaternary, Oligocene	4.5 km from MGR 210 (Quaternary)
Syczyn	none	TA = MCA (Cretaceous –Quaternary)		none	within MGR 407 (Cretaceous)

1	2	3	4	5	6
Wysin	none	TA (Quaternary)	MCA (Quaternary)	none	within MGR 116 (Quaternary)
Zawada	none	TA = MCA (Cretaceous)		none	within MGR 407 (Cretaceous)
Łebień	none	TA = MCA (Quaternary)		none	4 km from MGR 108 7.5 km from MGR 107 (Quaternary)
Gapowo	1 aquifer	TA (Quaternary)	MCA (Quaternary)	Quaternary	4.5 km from MGR 111 (Cretaceous) 18.5 from MGR 116 (Quaternary)

TA – top aquifer, MCA – main commercial aquifer, CA – secondary commercial aquifer, MGR – Main Groundwater Reservoir

Three out of seven test sites are located within Main Groundwater Reservoir areas (Table 4.3 and Fig. 4.2). The remaining four are located at a small distance from a MGR. All of the analysed reservoirs have been hydrogeologically proven according to applicable procedures, but buffer zones with land use injunctions or restrictions were not established by Regional Water Management Board Director's Regulation for any of them.

If the top aquifer is at the same time the main commercial aquifer (or the MGR), the impact on water quality was assessed jointly for the two aquifers. Brief descriptions of the tests made in each test site, including an assessment of the impact on the quality of water (according to the procedure shown on Fig. 4.3), are presented below. A more in-depth description of the tests and the results of particular test rounds is contained in final reports on survey delivery in each test site.



• test site location:
1 – Lubocino,
2 – Stare Miasto,
3 – Syczyn,
4 – Wysin, 5 – Zawada,
6 – Łebień, 7 – Gapowo

Fig. 4.2. Test site location within Main Groundwater Reservoirs.

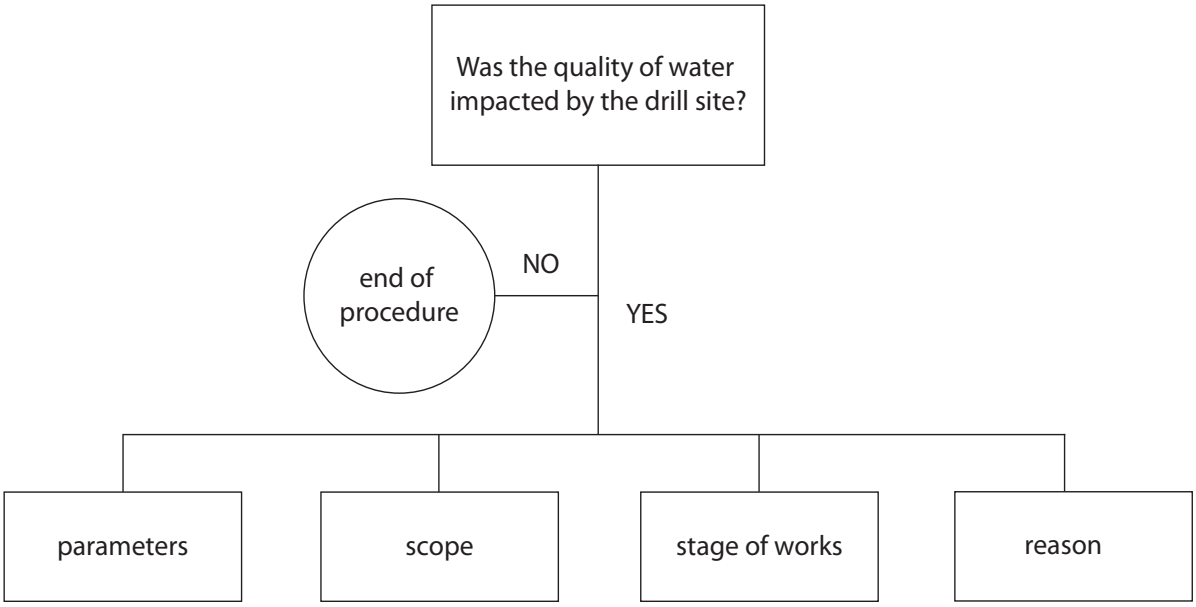


Fig. 4.3. Flowchart of the water quality impact assessment procedure.

Lubocino Test Site

Pollutants characteristic of shallow groundwater vulnerable to farming and human activities (mainly nitrogen compounds) were found in shallow perched aquifers. Due to the presence of potassium and anionic detergents in high amounts the groundwater was attributed to purity class IV or V. Their distribution in time and space reflects seasonal variability, which is probably contingent on field work cycles and the impact of domestic wastewater.

The tests of the main commercial aquifer (which is the top aquifer at the same time) have indicated that the groundwater is of good quality, a stable chemical composition and a majority of the tests made place it in groundwater quality class I or II. The Oligocene aquifer (Ol) was only tested at monitoring point SOH II-223/1 for mineralization, expressed as specific electrolytic conductivity (SEC), so as to establish the value of reference for an assessment of potential ascension of the highly mineralized deeper waters. In the samples collected at test round I, SEC was equal to 251 µS/cm, which is characteristic of groundwater quality Class I.

The quality of surface water reservoirs that are recharged by shallow circulation waters in the high plain area is average. Elevated concentrations of phenolic index and non-ionic detergents were found in these waters. An elevated concentration of phenols in these reservoirs may be due to high volumes of submerged organic matter, which can be inferred from a slightly acidic reaction of the water.

The tests of wastewater sampled from drainage tanks located within the drill site perimeter have revealed increased concentrations of several indices from drill site operations. Indices characteristic of the analysed process are: potassium, sodium, chlorides, aluminium, phenols and detergents. The wastes had no contact with the aquatic-soil environment and were managed in accordance with applicable regulations.

The so-far made studies did not reveal any significant difference between the quality of surface and ground waters in the Lubocino drill site area before (as-found status) and after fracture stimulation of the Lubocino-2H well. An extensive groundwater pollution was not found in drill site neighbourhood. The quality of water in the main source of supply (MCA) is good and at this stage of the survey no impact on the quality of water from unconventional oil and gas exploration was found. The top aquifer water, which is produced from hang-dug wells, is highly diversified in terms of quality which ranges from good to very poor. The investigation showed that these waters are polluted from sources located in immediate neighbourhood of the water wells.

The elevated concentrations of specific compounds testify to anthropogenic origin of the pollutants, mostly due to poor technical condition of the wells or inadequate waste management in the households. Considering a potential brackish water ascension from deeper strata (while process fluids are characterized by high concentrations of chlorides that enable tracking their migration), water samples from deep aquifers were control tested for mineral content and concentration of chlorides. The effects of mineralized water ascension from deep aquifers were not found in any of the samples.

Stare Miasto Test Site

Considering highly exceeded concentrations of anionic detergents, the water of the top aquifer was attributed to quality class IV and V (poor chemical status of water). In the samples of water collected from drainage water tanks, concentrations of anionic detergents ranged from 0.4 mg/l to 1.04 mg/l at all test rounds. The observed temporal and spatial diversity of anionic detergent concentrations in the top aquifer is associated, as revealed by the final test round of 2014, with farming operations in that area (fertilizing and spraying of chemicals), as well as with penetration of machinery washing agents or municipal wastewater from the drill site area. Concluding, the assessment of shallow aquifer status on completion of fracture stimulation and gas-flow testing operations at Stare Miasto 1/K well has revealed that the water is of poor quality and exceedances of the aforementioned indices indicate a highly anthropogenically altered aquatic-soil environment. A significant deterioration of water quality was noted in the spring seasons, when various pollutants flow from roads with runoff to the top aquifer.

Elevated concentrations of Fe^{2+} and NH_4^+ ions, TOC and exceedances of anionic detergents (definitely of anthropogenic origin) were found in the main commercial aquifer. Accordingly, the water in that aquifer have been attributed to quality class IV. In the subsequent test rounds, methane concentrations higher than in other test points were found in the water from that aquifer (in the range of 0.587 to 0.931 mg/l. Methane occurring in the groundwater is probably of biogenic origin (from decomposition of organic matter).

The status of surface water was assessed on completion of hydraulic fracture stimulation and gas-flow tests by collecting samples of water from an abandoned pit located north of the drill site. Comparing with the as-found status, high concentrations of anionic detergents, ranging from 0.59 to 0.88 mg/dm^3, were found at each test round. The detergents are unquestionably of anthropogenic origin and their presence is likely to result from short snow-melting spells in winter and the spring thaw. Like in the as-found status, other indices are largely within the range of surface water quality class II.

Laboratory tests and field observations have attested to a short-term and transitory impact of drill site operations on the quality of water in the top aquifer. Different temporal and spatial distribution patterns of higher anionic detergent concentrations, as noted in September 2012 and April 2013, should be attributed to the annual field fertilization cycle with inputs from drill site operations (social activities, application of maintenance, cleaning or tending agents, etc.). No drill site impact on the quality of water was found, although the high concentrations of detergents are undeniably of anthropogenic origin and reach the pit through the drainage network with melting snow. A technical problem involving a flowback fluid spill from the flare had no adverse effects on the shallow groundwater environment.

The Stare Miasto drill site was reclaimed in August 2014. One more test round was delivered following the site reclamation works in order to assess the environmental status on restoration of the initial intended use. The tests of the top aquifer made in September 2014 at the abandoned drill site revealed high concentrations of phenols which are most probably attributable to the site reclamation stage. It is highly probable that phenols reached the soil-aquatic environment at removal of the lining material that sealed the site ground. Considering a small affected area (drill site yard and drainage tanks only), as well as drainage base proximity, the impact is of a short term. On the other hand, anionic detergent concentrations are lower than in previous test rounds. The remaining water quality indices and their variability are not associated with drill site exploration or site reclamation operations. The water of deeper aquifers were attributed to quality class V due to high concentrations of arsenic (22.0 µg/l).

Syczyn Test Site

In the Syczyn test site area, the top aquifer is at the same time the main commercial aquifer. The results of water quality tests were not significantly different from those of the first test round. Locally reported high concentrations of potassium ions, nitrogen compounds and sulphates suggest local pollution from the lack of waste and wastewater management or inadequate land use in immediate water well proximity. As far as organic indices are concerned, slight variations in concentrations of C_2–C_{10} hydrocarbons and methane are attributable to different weather conditions prevailing at particular test rounds (natural variability).

Surface and ground water tests made in five rounds have not revealed any contaminants that derive from the drill site or are associated with drilling and fracture stimulation processes. Areal groundwater pollution was not found in drill site neighbourhood. The locally reported events of contamination are confined to the topmost aquifer in which high concentrations of sulphates and detergents of anthropogenic origin were found. These contaminants are probably associated with the lack of wastewater management and local pollution with domestic wastes. They may also be due to a poor technical condition of water wells or small uncontrolled discharges of waste and wastewater from the local households. Field observations have indicated that groundwater contamination occurs locally and is restricted to the farmstead perimeter.

Wysin Test Site

The water that is commercially produced from a Quaternary aquifer in the Wysin test site area is of good quality in terms of chemical composition (quality class I or II). Representative samples were collected from drilled water wells that produce water for the local public supply systems and from a source located at the foot of an escarpment in the Rutkownica River valley, about 2 km away of the drill site. The source is not exposed to external factors, such as immediate proximity of farmstead water wells. The tests indicate that the water is of good quality. Following a change in the strategy of Operator who refrained from delivery of subsequent exploration stages on drilling the well, the decision was made in consultation with Contracting Authority to discontinue the survey.

Zawada Test Site

In the Zawada test site area, the top aquifer is at the same time the main commercial aquifer. The groundwater status is good, but locally high concentrations of sulphates and detergents are found in the water from hand-dug farmstead wells. They are probably associated with a lack of wastewater management and local pollution with domestic wastes. They may also be due to a poor technical condition of water wells or small uncontrolled discharges of waste and wastewater from the local households. Field observations have indicated that the groundwater is only locally polluted. The tests made have not identified any areal contamination of the groundwater.

Surface water assessment for quality is based on the tests of samples collected from 2 water courses located north (downstream) of the drill site. Accordingly, the collected samples are representative of shallow water circulation. The results of tests are similar to those made in groundwater samples. Based on sample tests, the surface water was attributed to water quality class II (in accordance with Environment Minister's Ordinance of 9 November 2011 on *the classification of uniform surface water bodies and environmental quality standards for priority substances*).

In light of field surveys made and an analysis of survey results it is concluded that Operator's activities did not pose a risk to surface and ground water and, by the same, did not pollute the waters. Drill site operations have not affected the chemistry of waters in the neighbourhood of Zawada test site. The results of water sample tests for organic and inorganic indices made in the final test round (a year after hydraulic fracture stimulation of the well) are similar to those reported from previous test rounds. A slight decrease in methane concentrations was reported, but it should be emphasized that methane concentrations in the water are small and their variations reflect natural processes that occur in the soil-aquatic environment.

Łebień Test Site

The tested groundwater which is produced at all monitoring points in the Łebień test site area belongs to a single main commercial aquifer (MCA). Overall, groundwater status is poor in terms of

chemistry (quality class IV or locally class V) in the Łebień test site area, primarily due to elevated concentrations of nitrates and phosphates. The remaining indexes are within the ranges of water quality class I through III (i.e. good water status). Elevated concentrations of the aforementioned indexes are due to human activities, mainly those associated with farming operations. The tests made did not show any link between overall groundwater status and drill site operations or shale gas exploration processes. This conclusion is supported by the comparison of the tests made in water samples collected in 2011 before hydraulic fracture stimulation and subsequently under three test rounds (December 2013 through July 2014). The results of test rounds I-III are within the geochemical background for groundwater, as established in 2011. By the same it has been confirmed that drilling and fracture stimulation operations had not contaminated the groundwater and did not represent a risk to groundwater quality.

The first test round (December 2013) showed a change in water chemistry at test point 11 (water well no. 1 within the drill site perimeter) comparing to the test of July 2011. The concentrations of chlorides, sodium, calcium, bromides and the conductivity (SEC) were found to be significantly higher.

These results prompted the decision to deliver the next (second) test round (in April 2014) which confirmed a change in water chemistry, as detected in the previous test round. The concentrations of chlorides, sodium, calcium, bromides were found to be higher at test point 11 comparing with December 2013. However, the tests did not explain the reasons behind these results nor identify a potential source of the substances that caused an increase in concentrations of these parameters. Therefore, one more (the third) test round was delivered in July 2014, including an additional test point 9 (a monitoring well) located at the groundwater flow line, as established using the mathematical model. **The third test round showed significantly lower contents of chlorides, sodium, calcium, bromides and a SEC decrease in water sampled at test point 11, comparing to the results of round II.**

The tests of the water sampled at the monitoring well located beyond the drill site at the groundwater flow line (test point 19) for selected indices (chlorides, sodium, calcium and conductivity (SEC)) yielded concentrations similar to those reported from test point 11, thus confirming that they migrated southward along the pathway of groundwater outflow from the drill site, as established by mathematical modelling.

It should be emphasized that at all testing rounds (I though III) the top concentrations of chlorides, sodium, calcium and bromides, as well as the top specific conductivity (SEC) did not exceed at the test points 11 and 19 the thresholds established for waters of a good chemical status (quality class III). In other two monitoring wells (tests points 20 and 12), the reported values were similar to those characteristic of the analysed area. The tests made at the upstream-located monitoring well no. 20 and water well no. 2 have indicated that drill site operations were behind the changes in water chemistry.

An analysis of the mathematical model, as well as of specific concentrations and their variability at the test points in particular test rounds has indicated that the reason behind higher concentrations of these parameters had occurred during delivery of drill site operations between June 2009 and June 2013.

Considering test results, the nature of parameters with elevated concentrations, spatial distribution and temporal variability, geology, test point location and the then drill site layout, it should be assumed that the changes in groundwater chemistry were triggered by an incidental or short-term event that has occurred at the ground surface or at a shallow depth below the ground in the proximity of water well no. 1 (test point 11).

The temporal distribution of chemical indexes, transitory nature of changes in groundwater chemistry and the decrease in concentrations at the absence of an identified source of pollution testify to incidental nature of that event.

There are no grounds to speculate that the change in groundwater chemistry derives from drilling or existence of any of the two wells (LE-1 and LE-2H) located at the drill site. Therefore, it is reasonable to assume that the pollutants have penetrated with infiltrating water into the aquifer.

In light of an analysis of the tests made in 2011 and then in three test rounds it is obvious that the concentrations of a majority of the indices have not changed and are within typical background ranges.

On the other hand, a significant variability (increase) of the content of components that are characteristic of a pollutant such as brine water (e.g. process fluids or drill site de-icing agents) found in test points 11 and 19, indicates that concession Operator's activities in the drill site area resulted in a local transitory change in groundwater chemistry (still within quality class III), involving non-toxic compounds, which did not represent a threat to the overall chemical status of the groundwater.

Gapowo Test Site

Top aquifer water is of quality class V (mainly due to the presence of organic contaminants and their derivatives). Results of the test round made following hydraulic fracture stimulation operations have conform the previously established patchwork-like variability of groundwater quality indices, which may suggest point sources of groundwater pollution from inadequate wastewater management. Small farms prevail in the surveyed region. Based on a statistical analysis of organic and inorganic parameter concentrations it is concluded that the top aquifer water has been anthropogenically altered in terms of chemistry.

The water in deeper intra-moraine aquifers has been attributed to quality class IV, due to the content of organic substances and locally also of iron, potassium and nitrogen compounds. Higher concentrations of specific parameters are the consequence of man-made impact on the ground surface (mainly inadequate wastewater management and fragmented land use patterns). The identified cases of contamination are limited to shallow groundwater where high concentrations of sulphates and detergents, indicating man-made origin of pollutants, were reported. Significant differences were found between the first and second test round in commercial aquifers, especially in terms of anionic detergents. A two or three fold decrease in the content of anionic detergents was reported from the second intra-moraine aquifer.

In light of field surveys made and an analysis of survey results it is concluded that Operator's activities did not pose a risk to surface and ground waters and, by the same, did not pollute the waters. The variability of the parameters in the top and commercial aquifers, as reported from hydrogeochemical studies, is typical for Quaternary formations of the Polish Lowlands, while local exceedances of certain indices are associated with immediate neighbourhood of test points and land use patterns.

Surface water of the region are in good condition and the tested parameters are within the permitted levels, as specified by Environment Minister's Ordinance of 9 November 2011 *on the classification of uniform surface water bodies and environmental quality standards for priority substances*. In all groundwater samples the concentrations of volatile aromatic hydrocarbons (BTEX) were below the limit of detection.

Conclusions

In order to compare the results of water quality tests made in particular test sites at the same stage of operations (before and after fracture stimulation and, in the case of Stare Miasto, Syczyn, Zawada and Łebień after one or two years of fracture stimulation), average test data from particular stages of operations have been tabulated in the Table 4.4.. The indices that, in light of the tests made and an analysis thereof enable an assessment of the actual impact from shale gas exploration/production, have been included in the analysis. These indices have been proposed for the determination under long-term monitoring or for the studies of additional test sites (Chapter 5.5).

Table 4.4. Average values of the determinations made at selected test rounds in particular test sites

Test site		Lubocino		Stare Miasto			Syczyn			Wysin		Zawada			Łebień			Gapowo	
Aquifer		TA		TA			TA = MCA			TA		TA = MCA			TA = MCA			TA = MCA	
Index	Unit	Stage I	Stage II	Stage I	Stage II	Stage III	Stage I	Stage II	Stage III	Stage I	Stage II	Stage I	Stage II	Stage III	Stage I	Stage II	Stage III	Stage I	Stage II
		average		average			average			average		average			average			average	
pH	–	7.38	7.6	7.14	6.97	7.11	7.31	7.27	7.25	7.46	nt	7.09	7.3	7.37	7.88	nt	7.71	7.65	7.53
SEC	µS/cm	323.7	262	988	802	863	771	830	657	591	nt	1337	1102	544	281	nt	480	374	371
Na	mg\l	8.73	4.28	15.94	11.1	12.96	23.57	28.62	9.72	7.65	nt	37.9	30	3.85	6.2	nt	14.8	5.1	4.7
K		5.92	2.63	52.12	2.2	49	24.45	38.63	22.3	3.08	nt	2.8	2.6	1.1	0.9	nt	1.0	5.5	1.6
Ca		51.75	45.00	132.54	139.8	127.8	105.85	107.35	110	100.67	nt	206	160.9	91.6	47.8	nt	70	61.7	62.6
Cl		8.82	6.88	24.62	24.62	16.87	33.77	33.22	14.2	16.59	nt	70.5	64.6	16.5	15.1	nt	51.6	7.16	7.86
Sr		0.09	0.07	0.74	0.34	0.58	0.85	0.77	1.44	0.14	nt	0.79	0.71	0.36	0.065	nt	0.1	0.116	0.113
Br		nc	nc	nc	nc	nc	nc	nc	nc	nc	nt	nc	nc	nc	nc	nt	nc	nc	nc
B		0.0175	0.0125	0.09	0.07	0.09	0.09	0.14	0.06	0.02	nt	0.07	0.08	0.01	nc	nt	nc	0.01	0.01
Li		0.000717	0.000767	0.0129	0.0074	0.0118	0.0079	0.0065	0.0138	0.0039	nt	0.009	0.1	0.012	nc	nt	0.0048	0.005	0.0047
Phenolic index*		0.01383	0.11375	nc	nc	0.093	nc	0.01828	0.1295	0.1475	nt	nc	nc	0.061	nc	nt	no	0.0355	0.079
Oil index		0.0542	0.347	0.0667	0.02563	0.0108	0.0387	0.0306	nc	0.0374	nt	no	0.017	no	nc	nt	0.028	0.134	0.0239
Anionic detergents		0.260	0.160	0.3675	0.92	0.1375	0.3655	0.3155	0.2575	0.2025	nt	0.5	0.39	0.3	nc	nt	0.29	0.29	0.445
methane		0.00060	0.00105	0.03621	0.00143	0.00385	0.0035	0.0014	0.0021	0.0015	nt	0.0012	0.0013	0.0006	nc	nt	0.0016	0.0022	0.0105
BTEX		nc	nc	no	nc	nc	nc	nc	nc	nc	nt	nc	nc	nc	nc	nt	nc	nc	nc

Stage I Initial or as-found status
Stage II Status on completion of works by the Operator (after hydraulic fracture stimulation)
Stage III Follow-up monitoring (½ year or 2 years after hydraulic fracture stimulation – supplement)
nt – not tested (no fracture stimulation at Wysin site)
nc –not calculated (over 50% below the determination limit)

* **– low credibility results (further testing required)**

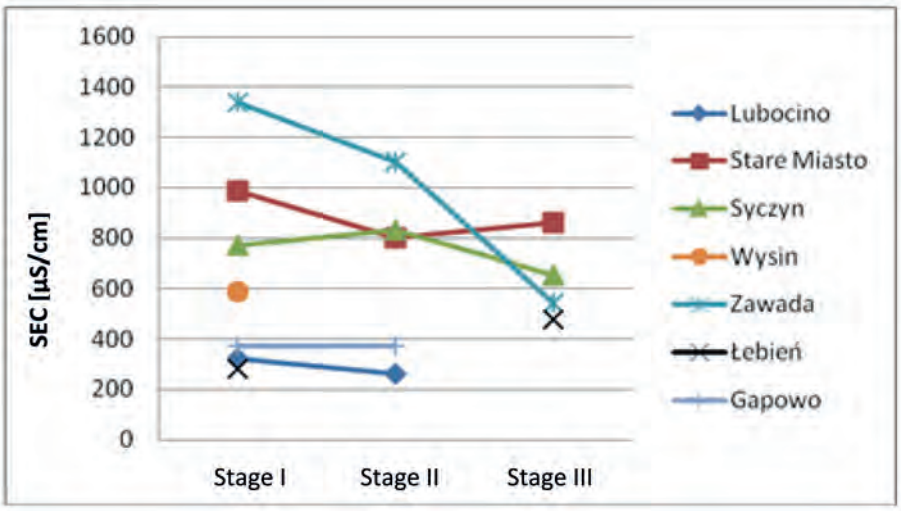


Fig. 4.4. Average specific electrolytic conductivity (SEC) at particular sampling stages (stage numbering as per Table 4.4).

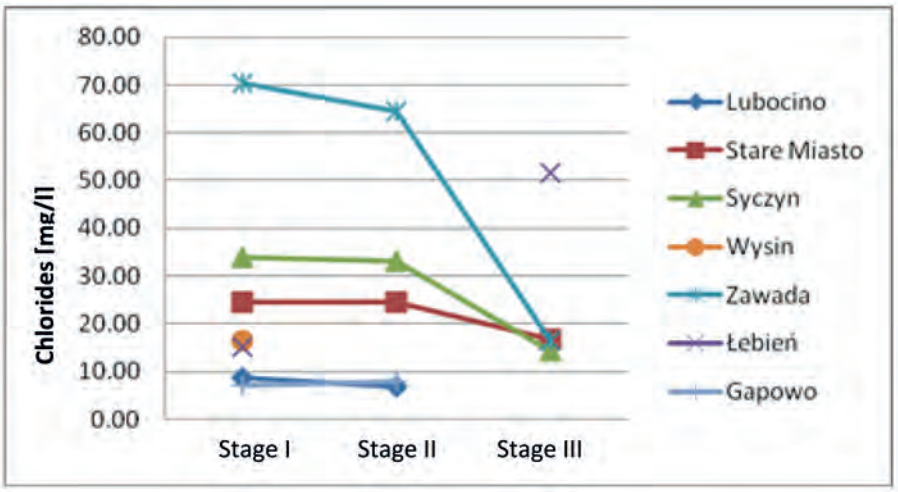


Fig. 4.5. Average chloride concentrations at particular sampling stages (stage numbering as per Table 4.4).

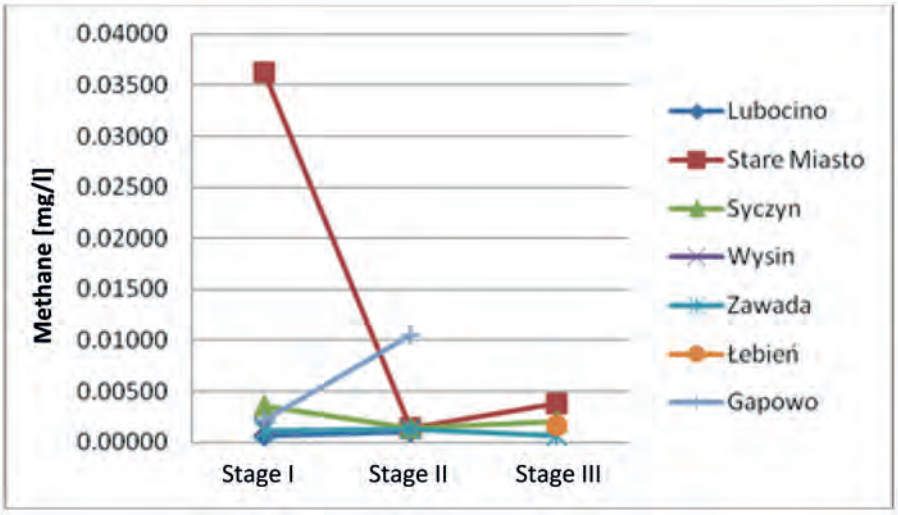


Fig. 4.6. Average methane concentrations at particular sampling stages (stage numbering as per Table 4.4).

A comparison of average determinations made before and after fracture stimulation at particular test sites does not reveal any meaningful changes in physicochemical water parameters. Similarly, no significant changes in test site impact indices were found after two years of hydraulic fracture stimulation.

Since no impact on both chemistry (quality) and quantitative status of the water was found in the area of concession Operators' activity, shale gas prospection and exploration operations had no an adverse impact on the main commercial aquifers. Special attention has been paid to Syczyn and Zawada that are located in the area of an open (largely non-isolated) MCA within a fractured medium. Nevertheless, no impact on the quality and reserves of these reservoirs was found in these two test sites.

4.4.2 The extent of the impact on quantitative status of the groundwater

An analysis of water withdrawals for hydraulic fracturing in relation to existing water management patterns in test site areas was made to assess the extent of impact from drill site operations on the quantitative status of groundwater. Safe yield reserves and unused (stand-by) reserves have been compared to the water withdrawals for the needs of particular drill sites (Table 4.5). The table shows that fracturing water withdrawals account for a small percentage share of all safe yield. Assuming that other users' requirements for water in 2013 and 2014 have been similar to the 2012 level, the withdrawals of water for fracturing purposes accounted for 0.045% of the safe yield. Accordingly, the operations had no adverse effects on the groundwater status and on water availability to other users. The existing reserves at particular Uniform Parts of Groundwater Bodies (UPGB) are capable of satisfying much higher demand from more extensive exploration, appraisal and production operations.

Table 4.5. Groundw ater reserves versus water consumption for fracturing purposes

Test site	UPGB	Safe yield	Stand-by reserve	Fracturing water withdrawal	% of safe yield used for fracturing purposes	% Of stand-by reserve used for fracturing purposes
		(as of 2012)				
		000 m³/year	000 m³/year	000 m³	%	%
Lubocino	13	110 650	56 161	7.967	0.007	0.014
Stare Miasto	19	111 930	103 737	3.212	0.003	0.00319
Syczyn	87	79 034	66 476	37.849	0.05	0.057
Wysin	30	119 951	107 375	none	No fracturing	No fracturing
Zawada	107	256 792	213 472	1.284	0.0005	0.0006
Łebień	11	208 828	190 539	17.322	0.008	0.009
Gapowo	13	110 650	56 161	25.360	0.023	0.045

4.4.3 Penetration of reservoir and process fluids to the aquifers

Upward propagation of hydraulically-induced fractures

The scenario of groundwater contamination with reservoir and/or process fluids may potentially materialize, if a hydraulic stimulation-induced fracture propagates into strata that are in direct hydrodynamic contact with the freshwater aquifers. A fracture may effectively propagate to the ground surface only through natural fractures and faults that dissect sealing complexes that normally overly the gas-bearing shales. However, the risk of upward vertical migration of reservoir and process fluids is minimized by the following geomechanical factors (Abousleiman et al., 2007; Barree, Gilbert, 2009; DECC, 2014; De Gennaro, 2011; Engelder, Gold, 2008; Jarosiński, 1999; Kratz et al., 2012; McLennan et al., 2011; Sarker, Batzle, 2008; Sarker, Batzle, 2008; Suorez-Rivera, 2011; Zoback, 2010):

- The presence of beds with strong mechanical contrasts causes significant changes in lateral stress at particular beds. Beds with elevated elasticity moduli have higher horizontal stress values that limit upward propagation of fractures, thus forming natural geomechanical barriers.
- Bedding planes that are brittle due to a higher content of clay represent another effective barrier to vertical fracture propagation. Hydraulically-induced fractures tend to branch or die out at the bed planes so that upward propagation of fractures is less effective.
- The closer to the ground surface the lower is vertical stress (Sv) and more likely is the occurrence of reverse-slip fault regime, which promotes occurrence of horizontal fractures, most often propagating along the bedding plane and unable to propagate vertically.
- Conductivity of hydraulically-induced vertical fractures is also limited by inefficient upward transport of proppant. Unpropped fractures tend to close after fracturing operation, especially if a shear offset (evidenced by micro-seismic events) occurs along the fracture plane.
- A significant pressure drop during stimulation from both flow resistance in the distal fracturing zone and, in the case of upward transport, hydrostatic pressure of the fracturing fluid column. If the fractures are more than 300 m high (i.e. are exceptionally high), hydrostatic pressure falls by more than 3 MPa, which is a significant share of the reservoir overpressure.
- As the hydraulically-induced network of fractures propagates in the rocks, the volume of fluid required for continued fracture propagation suddenly increases, due to both higher capacity of the fractures (getting wider upward) and fluid infiltration to more permeable layers, of which intensity increases with expanding fluid exchange interface between the rock matrix and the fracture. The latter mechanism is effective in accumulations without pore overpressures, such as those prevailing in Poland.

The action of all of the above factors combined prevents upward propagation of fractures that may put commercial aquifers at the risk of contamination. The actual vertical range of hydraulically-induced fractures in shale oil and gas exploration is shown in a statement based on micro-seismic and inclinometer monitoring made at thousands of fracturing operations in the Barnett, Marcellus, Woodford and Eagle Ford shale basins (Fisher, Warpinski, 2011). This statement is reliable as these basins differ significantly in terms of lithology, fracture systems and contemporary stress directions, magnitudes and regimes. As shown on Fig. 4.7, vertical range of fractures above the perforated well depth only exceptionally was in excess of 300 m and in none of the thousands fracturing jobs made a vertical fracture was longer than 600 m. In the Woodford and Eagle Ford Basins the fractures never exceeded 250 m above the interval of perforation. It should be noted that the cases of fracturing fluid penetration into conductive fault zones, which greatly increases the vertical range of hydraulically-induced fractures, are also included in this set of data. The statements shown in Fig. 4 demonstrate that the shallower the fractured complex, the smaller is the vertical range of hydraulically-induced fractures. Therefore, the mechanisms that restrict upward propagation of fractures prove to be very effective in practice. Despite a huge variability of fracturing depth in the U.S. (from 3.5 to 1 km, not a single event of fracture propagation into commercial aquifer was reported. It should be reminded at this point that the height of hydraulically-induced fractures, as established by micro-seismic monitoring, did not exceed 80 m at Lubocino-2H well. In addition to fracture propagation, which is accompanied by micro-seismic vibrations, fracturing and reservoir fluids may slowly seep after fracture stimulation – a phenomenon that does not involve micro-seismic vibrations and ground surface deformations that are detected by inclinometer monitoring Such events may occur at a limited scale and only in tectonic zones with natural ascending circulation.

The conditions for upward migration of fracturing and reservoir fluids

The above overview demonstrates that shallow commercial aquifers could be contaminated by high-volume hydraulic fracture stimulation only in the event of coinciding occurrence of several adverse factors:

1. very small depth to the target accumulation, at which small pressures and small fracturing fluid volumes are required for propagation of hydraulically-induced fractures, comparing to fracturing operations made at bigger depths;
2. occurrence of near-surface stress regimes that stimulate propagation of vertical fractures;

3. penetration of large volumes of fracturing fluid into conductive fault zones;
4. naturally-formed ascending circulation of fluids in such fault zone;
5. operator's mistake involving continued fracture stimulation at uncontrolled spill of the fluid out of the accumulation – which is normally clearly indicated by pressure and pump output curves.

The first of the above conditions is not met by any the analysed wells, as the shallowest reservoir interval is located at a depth of approx. 2700 m (Syczyn OU-2K well). This depth is comparable to those found in the deepest U.S. shale plays, which are also considered as the safest in terms of potential spills.

As far as the second condition is considered, the stress regime prevailing in Poland at smaller depths has not been investigated. Therefore, the worst case scenario of normal and strike-shift faults that promote propagation of vertical fractures (Jarosiński, 2006) is tentatively assumed. Hydraulically transmissive faults are the key risk factor, but it should be noted that considering non-homogenous internal structure of fault zones their transmissivity is variable and almost impossible to determine due to invariably insufficient data. It is generally accepted that fault tightness is promoted by: continuity of sealing beds between tectonic bocks; a higher content of sealing rocks squeezed into the faulted zones; a big depth to the dislocations that helps to close them with lithostatic pressure; and a low intensity of recent tectonic deformations in a given area that is expressed by the absence of seismic activity.

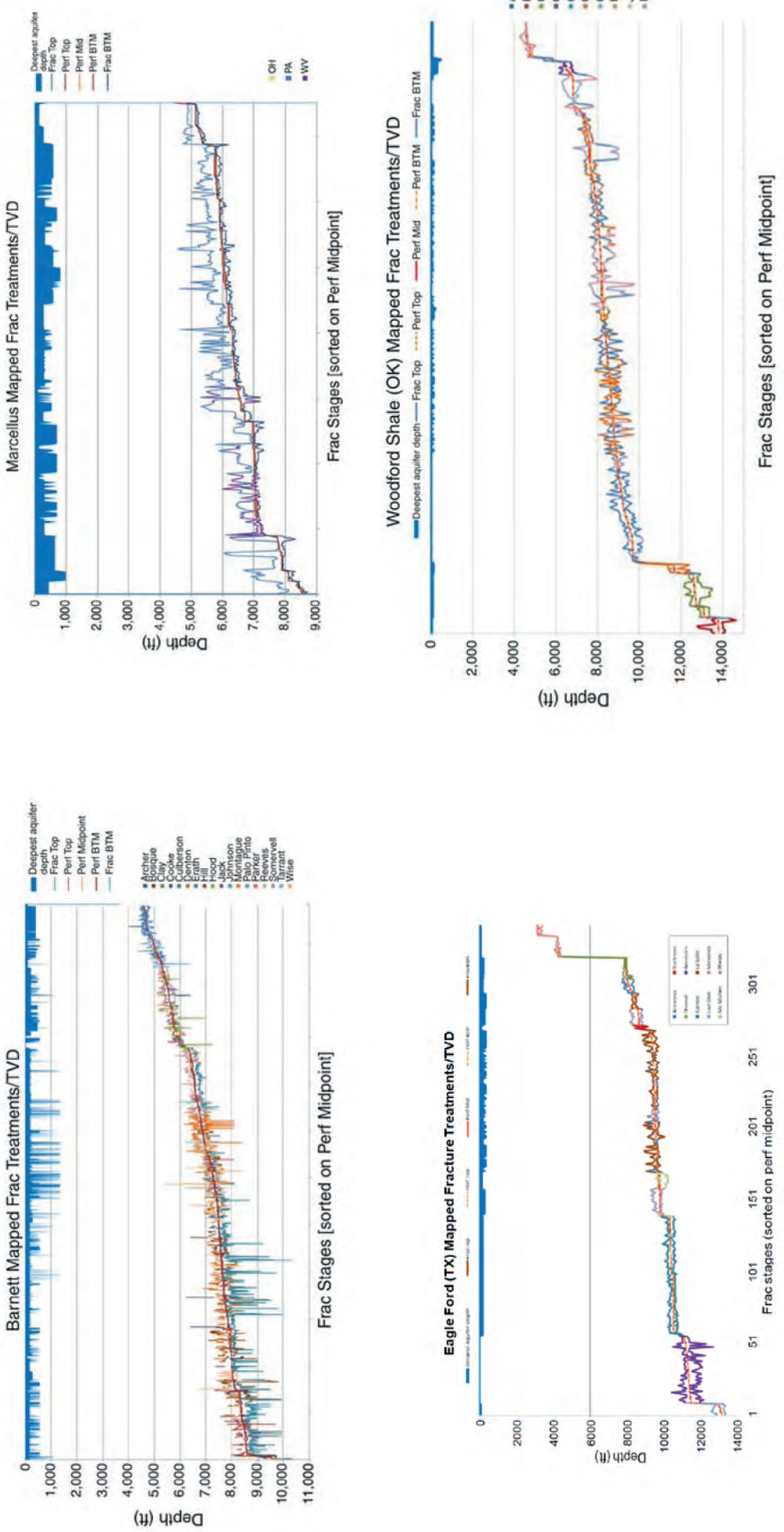


Fig. 4.7. Statement of vertical range of hydraulically-induced fractures, based on micro-seismic and inclinometer monitoring in four U.S. shale plays: Barnett, Marcellus, Woodford and Eagle Ford (after Fisher & Warpinski, 2011).

In the case of wells analysed under this project, hydraulically transmissive faults were not found (wherever an estimate of fault zone transmissivity was possible). Recent seismic activity was not reported, either.

Information about potential occurrence of natural ascending flow within the fault zones is not available. Nevertheless, a sustained occurrence of that flow would result in increased salinity of subsurface aquifers long before fracturing operations, which was not found at the stage of as-found status determination.

A potential human error or failure of safety equipment must be considered at any fracture stimulation project. However, in the analysed cases there are inherent serious technical limitations, such as top output of pumps and limited fracturing fluid volume, that minimize the consequences of potential errors.

In the case of the analysed exploratory wells, all of the key factors favour rock mass integrity. Therefore, an operator's error (to a reasonable extent) does not carry a potential risk of groundwater pollution. This conclusion is equally true for potential migration of pollutants in the near-well zone.

Potential migration of fracturing fluid along the near-well zone may occur in the event of inadequate casing cementation and a failure to ensure well integrity. However, there are several mandatory tests (including tightness tests of each casing string lowered to the borehole, CBL – cement bond log, diagnostic tests before fracture stimulation) that are verified by competent authorities which impose a strict regime of fracturing operations. Operators ensure compliance by applying adequate techniques of cementation and a proper construction of wells. Adequate well completion, inspection and control of particular operations eliminate these risks, too.

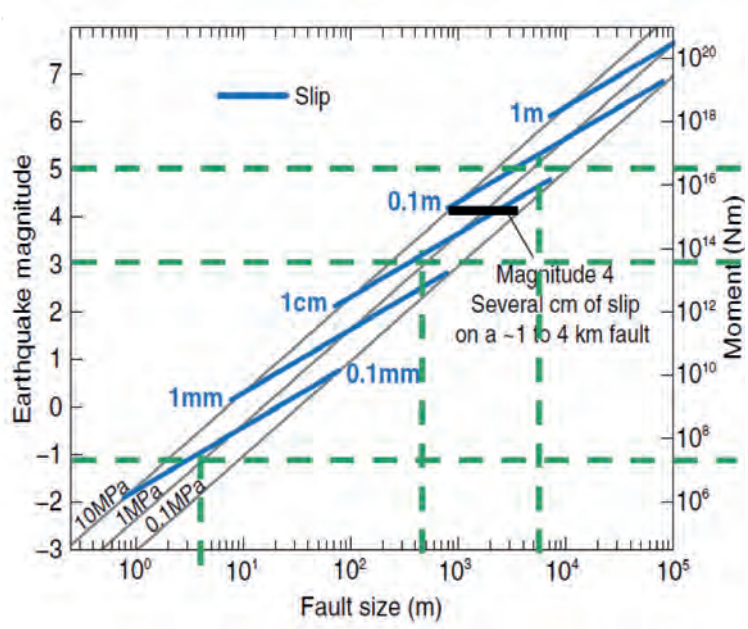
Concluding, for each of the investigated test sites there are no reasons to suspect the risk of fracturing or reservoir fluid penetration into commercial aquifers as a result of fracture stimulation. Considering the geology of prospective shale formations in Pomerania, this scenario is even in theory unrealistic, as the fault offsets there are utterly small comparing with the thickness of the sealing complexes. The latter are exceptionally effective in terms of sealing properties due to a significant lateral continuity, thickness and low (but insufficiently proved) permeabilities. In the Lublin Region, the probability of commercial aquifer contamination from fracture stimulation is small, mainly due to the considerable thickness of the Silurian complex and its extensive continuity. However, homogeneity of its structure could not be assessed due to insufficient data. The other younger sealing complexes in the Lublin Region are not continuous. Moreover, as some fault displacements exceed the thickness of the sealing strata, the degree of sealing should be assessed on a case by case basis, especially if the Zechstein screen is absent. In the analysed test sites, the clearance from major fault zones is big enough to preclude the risk of process and reservoir fluid escape as a result of fracturing operations.

4.5 Ground surface: the risk of induced seismicity

The total energy of a single hydraulic fracturing stage is equal to the energy of a magnitude 3 (M3) seismic event, i.e. the smallest seismic tremor that is perceptible to a man standing on the ground surface. However, in the case of a natural earthquake, the energy is released over a period of a few seconds and focuses at a single slip plane, while the fracturing energy is released in a period of several thousands of seconds at distributed displacement planes, expressed as a cloud of micro-seismic events. Moreover, the energy of the strongest micro-seismic event (M-1) is about 1 million fold weaker than the weakest seismic event which is perceptible to man on the ground surface. It should be emphasized that the energy of an eartquake capable of damaging erected structures is 1000 fold bigger than that of a perceptible seismic event.

Therefore, the only mechanism that may pose a risk on the ground surface is an induced natural seismic earthquake that would release the energy of tectonic deformations, as accumulated in the rocks. A shale fracturing-induced natural seismic event was reported from Blackpool in the United Kingdom (DECC, 2014).In that case, an earthquake of a low magnitude (M 2.3) did not cause any damage. The key reason behind inducing the seismic event with the technological

process was, in this particular case, an increase in the pore pressure that reduced the effective stress. According to Mohr-Coulomb failure criterion, a fault slip may occur at the lowest level of the accumulated energy. A fracturing-triggered seismic event may only be weaker than natural seismic event occurring in the affected region, insofar as due to pressure increase at fracture stimulation the energy may be released at an inferior effective stress level. Accordingly, induced seismic event is not an additional risk factor as it may only expedite earthquake occurrence in a particular area.



Energy levels of earthqakes perceptible on the ground surface and of fracturing-induced micro-seismic events

The weakest earthquakes that are destructible to structures

300 MWh – the weakest perceptible

3 kWh – the strongest micro-seismic events

30 Wh – the weakest recorded micro-seismic events

Fig. 4.8. Relationships between earthquake magnitude, slip length in the centre of the earthquake and the slip plane (fault) length, after Zoback & Gorelick (2012).

A fault at a near-critical stress state must occur in the fracture-stimulated interval in order to induce an earthquake. In order for the earthquake to be perceptible on the ground surface, the fault should be of adequate size, as a minimum several hundred metres long, so as to enable accumulation and release of the energy required (see Fig. 4.8). The fault must be over 1 km long to induce a damaging earthquake (~M 5). It should be emphasized that the pore pressure increase by several MPa (which is a realistic figure for fracture stimulation) covers an area of several hundred meters. Therefore, even assuming the worst case of critically stressed faults, an earthquake above M 4 can hardly be triggered. Stronger earthquakes of magnitudes M 4.7 and M 5.3 (in Arkansas and Colorado/New Mexico, respectively) were induced as a result of multi-year injection of process fluids (including coalbed fracturing fluids) for underground storage in reservoir formations (Zoback & Gorelick, 2012). Accordingly, the earthquakes were not connected with fracture stimulation. Moreover, these U.S. regions are much more seismically active than our sites under investigation. In the United Kingdom, it is recommended to discontinue shale fracturing operations if earthquake magnitude is in excess of M 0.5 (DECC, 2014).

A considerable depth to the prospective shale formations in Poland enhances significantly the safety of fracturing operations, while contributing heavily to potential development costs. The tested areas are among the least seismically active in Europe so that the risk of perceptible earthquake occurrence in extremely low. The risk is likely to be lower in Pomerania than in the Lublin Region. The absence of any major fault zones near the boreholes is not accidental. Instead, it is a general rule followed by exploration companies. Based on a thorough seismic survey drilling locations are selected so as to avoid any fault zones in order to enhance effectiveness of fracture stimulation in gas-bearing shale rocks. Therefore, the faults are avoided not only for safety concerns but also for economic reasons, which makes it a good case of synergy between investor's interest and environmental benefits.

4.6 Assessment on impact on protected areas

The assessment of impact from shale gas prospection and exploration operations in investigated locations on environmentally valuable areas is presented in the Table 4.6. The analysis covered the following protected areas within a radius of 15 km from the drill sites: nature reserves, national parks, scenic parks, protected landscape areas and Natura 2000 sites – special habitat protection areas and special bird protection areas. The location of protected areas with regard to the nearest drill site is shown in the table along with water-dependent ecosystems, based on the database by Jarzombkowski F. et al., 2009. The following test site parameters are included: predominant wind direction and groundwater flow direction. The assessment of particular impacts is based on the following assumptions that reflect the results of the tests made under this Project:

- NOISE: potential impact at a distance of up to 500 m from the drill site
  - 0: distance from the area to the drill site >500 m,
  - 1: distance from the area to the drill site <500m;
- TRANSPORT: a heavier vehicular traffic at the road section from the drill site to the nearest provincial road or to the junction of provincial roads
  - 0: The above defined heavy traffic road section does not intersect the area or is not located in its immediate neighbourhood,
  - 1: The above defined heavy traffic road section intersects the area or is located in its immediate neighbourhood;
- WATERS: water-dependent ecosystems are located in the direction of water flow from the drill site within the range of the potential time of migration
  - 0: the area is not located in the water flow direction or water-dependent ecosystems are not found in the area located in the water flow direction,
  - 1: the area is located in the water flow direction and water-dependent ecosystems are present in the area;
- ATMOSPHERE: potential impact at a distance of up to 1000 m from the drill site
  - 0: the area is located out of predominant wind direction or at a distance > 1000 m
  - 1: the area is located in predominant wind direction at a distance < 1000 m

The analysis did not reveal an impact on the protected areas other than Puszcza Darżlubska and Chełm Protected Landscape Areas, due to a long distance from the drill sites. As Lubocino and Syczyn drill sites are located within protected landscape areas, their operations may have potentially a short-term adverse effect on the following environmental compartments: the atmosphere (considering the predominant wind direction) and the water (considering direction and rate of flow), as well as may increase the level of noise. Also transport may have an adverse effect on the atmosphere and sound levels in protected areas that are located near the analysed drill sites. Considering drill site location in environmentally valuable areas, the Operator have obtained decisions on environmental preconditions for the projects and agreed project implementation conditions before drill site development.

Table 4.6. Analysis of impact on natural areas protected by the law from selected aspects of unconventional oil and gas exploration

TEST SITE			PROTECTED AREA					POTENTIAL IMPACT			
Test site No	GROUND WATER FLOW DIRECTION	PREDOMINANT WIND DIRECTION	RANK	NAME	DISTANCE FROM THE DRILL SITE	DIRECTION TO THE DRILL SITE	WATER-DEPENDENT ECOSYSTEMS [1)]	NOISE	TRANS-PORTATION	WATER	AIR
			A Natura 2000 Special habitat protection areas B Natura 2000 Special bird protection areas C protected landscape area D Scenic Park E National Park F Reserve					0 BRAK 1 MOŻLIWE			
1	SW	S, SW	B	Puszcza Darżlubska PLB220007	5.09	SE	YES	**0**	**1**	**0**	**0**
1	SW	S, SW	B	Bielawskie Błota PLB220010	8.40	NE	YES	**0**	**0**	**0**	**0**
1	SW	S, SW	B	Lasy Lęborskie PLB220006	9.74	SW	YES	**0**	**0**	**1**	**0**
1	SW	S, SW	B	Przybrzeżne wody Bałtyku PLB990002	12.62	N	NO	**0**	**0**	**0**	**0**
1	SW	S, SW	A	Trzy Młyny PLH220029	1.92	NE	YES	**0**	**1**	**0**	**0**
1	SW	S, SW	A	Opalińskie Buczyny PLH220099	3.46	W	NO	**0**	**0**	**0**	**0**
1	SW	S, SW	A	Orle PLH220019	6.28	S	YES	**0**	**0**	**0**	**0**
1	SW	S, SW	A	Bielawa i Bory Bażynowe PLH220063	8.49	NE	YES	**0**	**0**	**0**	**0**
1	SW	S, SW	A	Piaśnickie Łąki PLH220021	10.06	NW	YES	**0**	**0**	**0**	**0**
1	SW	S, SW	A	Widowo PLH220054	12.21	N	NO	**0**	**0**	**0**	**0**
1	SW	S, SW	A	Jeziora Choczewskie PLH220096	12.64	W	NO	**0**	**0**	**0**	**0**
1	SW	S, SW	A	Wejherowo PLH220084	14.37	SE	NO	**0**	**0**	**0**	**0**
1	SW	S, SW	A	Białogóra PLH220003	14.97	NNW	YES	**0**	**0**	**0**	**0**
1	SW	S, SW	C	Puszczy Darżlubskiej	0.00	0	YES	**1**	**1**	**1**	**1**
1	SW	S, SW	C	Pradoliny Redy–Łeby	5.40	SSW	YES	**0**	**0**	**0**	**0**
1	SW	S, SW	C	Nadmorski	7.38	N	YES	**0**	**0**	**0**	**0**
1	SW	S, SW	C	Choczewsko–Saliński	10.40	W	YES	**0**	**0**	**0**	**0**

TEST SITE			PROTECTED AREA					POTENTIAL IMPACT			
Test site No	GROUND WATER FLOW DIRECTION	PREDOMINANT WIND DIRECTION	RANK	NAME	DISTANCE FROM THE DRILL SITE	DIRECTION TO THE DRILL SITE	WATER-DEPENDENT ECOSYSTEMS [1)]	NOISE	TRANS-PORTATION	WATER	AIR
1	SW	S, SW	D	Nadmorski Park Krajobrazowy	9.91	N	YES	**0**	**0**	**0**	**0**
1	SW	S, SW	D	Trójmiejski Park Krajobrazowy	14.15	SE	NO	**0**	**0**	**0**	**0**
1	SW	S, SW	F	Źródliska Czarnej Wody – otulina	2.47	NE	YES	**0**	**0**	**0**	**0**
1	SW	S, SW	F	Źródliska Czarnej Wody	2.96	NE	YES	**0**	**0**	**0**	**0**
1	SW	S, SW	F	Darzlubskie Buki	8.30	SEE	YES	**0**	**0**	**0**	**0**
1	SW	S, SW	F	Zielone	9.14	N	YES	**0**	**0**	**0**	**0**
1	SW	S, SW	F	Bielawa	9.44	NE	YES	**0**	**0**	**0**	**0**
1	SW	S, SW	F	Długosz Królewski w Wierzchucinie	10.83	NNW	YES	**0**	**0**	**0**	**0**
1	SW	S, SW	F	Widowo	12.21	N	NO	**0**	**0**	**0**	**0**
1	SW	S, SW	F	Piaśnickie Łąki	12.23	NNW	YES	**0**	**0**	**0**	**0**
2	NW	W, NW	B	Lasy Iławskie PLB280005	6.25	SSE	YES	**0**	**1**	**0**	**0**
2	NW	W, NW	A	Ostoja Iławska PLH280053	6.76	SSE	YES	**0**	**1**	**0**	**0**
2	NW	W, NW	A	Aleje Pojezierza Iławskiego PLH280051	9.89	SSW	YES	**0**	**1**	**0**	**0**
2	NW	W, NW	A	Mikołajki Pomorskie PLH220076	12.74	SWW	YES	**0**	**0**	**0**	**0**
2	NW	W, NW	C	Rzeki Dzierzgoń	0.06	N, NE, E, SE	NO	**1**	**1**	**0**	**1**
2	NW	W, NW	C	Jeziora Dzierzgoń	4.60	SWW	NO	**0**	**0**	**0**	**0**
2	NW	W, NW	C	Pojezierza Iławskiego – część A i B	7.24	S	YES	**0**	**1**	**0**	**0**
2	NW	W, NW	C	Rzeki Liwy	12.07	SW	NO	**0**	**0**	**0**	**0**
2	NW	W, NW	C	Jeziora Drużno	12.12	NE	NO	**0**	**0**	**0**	**0**
2	NW	W, NW	D	Park Krajobrazowy Pojezierza Iławskiego	6.41	SSE	YES	**0**	**1**	**0**	**0**
2	NW	W, NW	F	Jezioro Gaudy	12.23	SSE	YES	**0**	**0**	**0**	**0**
3	W	W, SW	B	Bagno Bubnów PLB060001	5.27	NNE	YES	**0**	**0**	**0**	**0**
3	W	W, SW	B	Polesie PLB060019	10.45	NNW	YES	**0**	**0**	**0**	**0**

TEST SITE			PROTECTED AREA					POTENTIAL IMPACT			
Test site No	GROUND WATER FLOW DIRECTION	PREDOMINANT WIND DIRECTION	RANK	NAME	DISTANCE FROM THE DRILL SITE	DIRECTION TO THE DRILL SITE	WATER-DEPENDENT ECOSYSTEMS [1)]	NOISE	TRANS-PORTATION	WATER	AIR
3	W	W, SW	A	Ostoja Poleska PLH060013	5.27	N	YES	**0**	**0**	**0**	**0**
3	W	W, SW	A	Dobromyśl PLH060033	6.95	SW	YES	**0**	**0**	**0**	**0**
3	W	W, SW	A	Jeziora Uściwierskie PLH060009	8.50	NW	YES	**0**	**0**	**0**	**0**
3	W	W, SW	A	Serniawy PLH060057	9.28	NE	YES	**0**	**0**	**0**	**0**
3	W	W, SW	A	Sawin PLH060068	10.31	E	NO	**0**	**0**	**0**	**0**
3	W	W, SW	A	Bachus PLH060056	12.38	E	YES	**0**	**0**	**0**	**0**
3	W	W, SW	A	Nowosiółki (Julianów) PLH060064	12.92	SSE	YES	**0**	**0**	**0**	**0**
3	W	W, SW	A	Pawłów PLH060065	13.27	SSW	YES	**0**	**0**	**0**	**0**
3	W	W, SW	A	Krowie Bagno PLH060011	14.22	N	YES	**0**	**0**	**0**	**0**
3	W	W, SW	A	Stawska Góra PLH060018	15.00	SE	NO	**0**	**0**	**0**	**0**
3	W	W, SW	C	Chełmski Obszar Chronionego Krajobrazu	0.00	0	NO	**1**	**1**	**1**	**1**
3	W	W, SW	C	Poleski Obszar Chronionego Krajobrazu	8.50	NNW	YES	**0**	**0**	**0**	**0**
3	W	W, SW	C	Pawłowski Obszar Chronionego Krajobrazu	13.19	SSW	NO	**0**	**0**	**0**	**0**
3	W	W, SW	D	Chełmski Park Krajobrazowy	8.35	E	YES	**0**	**0**	**0**	**0**
3	W	W, SW	D	Poleski Park Krajobrazowy	12.48	NNW	YES	**0**	**0**	**0**	**0**
3	W	W, SW	D	Park KrajobrazowyPojezierze Łęczyńskie	13.11	NW	YES	**0**	**0**	**0**	**0**
3	W	W, SW	E	Poleski Park Narodowy	5.26	NNE	YES	**0**	**0**	**0**	**0**
3	W	W, SW	F	Jezioro Świerszczów	6.29	NW	YES	**0**	**0**	**0**	**0**
3	W	W, SW	F	Serniawy	9.28	NE	YES	**0**	**0**	**0**	**0**
3	W	W, SW	F	Bachus	12.38	NE	YES	**0**	**0**	**0**	**0**
3	W	W, SW	F	Stawska Góra	15.00	SE	NO	**0**	**0**	**0**	**0**
4	N	W, NW	B	Bory Tucholskie PLB220009	13.79	SW	YES	**0**	**0**	**0**	**0**
4	N	W, NW	A	Dolina Środkowej Wietcisy PLH220009	3.40	NWW	YES	**0**	**1**	**0**	**0**

TEST SITE			PROTECTED AREA					POTENTIAL IMPACT			
Test site No	GROUND WATER FLOW DIRECTION	PREDOMINANT WIND DIRECTION	RANK	NAME	DISTANCE FROM THE DRILL SITE	DIRECTION TO THE DRILL SITE	WATER-DEPENDENT ECOSYSTEMS [1)]	NOISE	TRANS-PORTATION	WATER	AIR
4	N	W, NW	A	Lubieszynek PLH220074	4.36	W	NO	**0**	**1**	**0**	**0**
4	N	W, NW	A	Zielenina PLH220065	4.61	NE	NO	**0**	**0**	**0**	**0**
4	N	W, NW	A	Guzy PLH220068	5.55	NNE	NO	**0**	**0**	**0**	**0**
4	N	W, NW	A	Szumleś PLH220086	5.73	NNW	NO	**0**	**0**	**0**	**0**
4	N	W, NW	A	Szczodrowo PLH220101	5.87	NEE	NO	**0**	**0**	**0**	**0**
4	N	W, NW	A	Dolina Wierzycy PLH220094	6.21	S–SE	YES	**0**	**0**	**0**	**0**
4	N	W, NW	A	Przywidz PLH220025	8.34	NNE	NO	**0**	**0**	**0**	**0**
4	N	W, NW	A	Wilcze Błota PLH220093	13.25	SW	YES	**0**	**0**	**0**	**0**
4	N	W, NW	A	Wielki Klincz PLH220083	13.38	W	NO	**0**	**0**	**0**	**0**
4	N	W, NW	A	Piotrowo PLH220091	13.48	NW	YES	**0**	**0**	**0**	**0**
4	N	W, NW	A	Pomlewo PLH220092	14.41	NNE	NO	**0**	**0**	**0**	**0**
4	N	W, NW	A	Huta Dolna PLH220089	14.56	NNE	NO	**0**	**0**	**0**	**0**
4	N	W, NW	A	Dąbrówka PLH220088	14.76	NW	NO	**0**	**0**	**0**	**0**
4	N	W, NW	C	Doliny Wietcisy	0.71	E	YES	**0**	**1**	**0**	**0**
4	N	W, NW	C	Doliny Wierzycy	3.73	S	YES	**0**	**0**	**0**	**0**
4	N	W, NW	C	Polaszkowski	5.93	SW	NO	**0**	**0**	**0**	**0**
4	N	W, NW	C	Przywidzki	6.79	NE–W–S	NO	**0**	**0**	**0**	**0**
4	N	W, NW	C	Borów Tucholskich	12.62	SW	YES	**0**	**0**	**0**	**0**
4	N	W, NW	D	Kaszubski Park Krajobrazowy	13.46	NW	YES	**0**	**0**	**0**	**0**
4	N	W, NW	F	Brzęczek	5.18	S	NO	**0**	**0**	**0**	**0**
4	N	W, NW	F	Orle nad Jeziorem Dużym	7.81	SW	NO	**0**	**0**	**0**	**0**
4	N	W, NW	F	Wyspa na Jeziorze Przywidz	11.85	NNE	NO	**0**	**0**	**0**	**0**
5	NE	S, SW, NW	B	Roztocze PLB060012	3.26	S	YES	**0**	**0**	**0**	**0**

TEST SITE			PROTECTED AREA					POTENTIAL IMPACT			
Test site No	GROUND WATER FLOW DIRECTION	PREDOMINANT WIND DIRECTION	RANK	NAME	DISTANCE FROM THE DRILL SITE	DIRECTION TO THE DRILL SITE	WATER-DEPENDENT ECOSYSTEMS [1)]	NOISE	TRANS-PORTATION	WATER	AIR
5	NE	S, SW, NW	B	Ostoja Nieliska PLB060020	5.07	WN	YES	**0**	**0**	**0**	**0**
5	NE	S, SW, NW	B	Dolina Górnej Łabuńki PLB060013	9.40	SE	YES	**0**	**0**	**0**	**0**
5	NE	S, SW, NW	A	Niedzieliski Las PLH060092	3.96	S	NO	**0**	**0**	**0**	**0**
5	NE	S, SW, NW	A	Niedzieliska PLH060044	4.74	SW	NO	**0**	**0**	**0**	**0**
5	NE	S, SW, NW	A	Kąty PLH060010	6.63	S	NO	**0**	**0**	**0**	**0**
5	NE	S, SW, NW	A	Doliny Łabuńki i Topornicy PLH060087	7.25	SE	YES	**0**	**0**	**0**	**0**
5	NE	S, SW, NW	A	Hubale PLH060008	7.27	SE	YES	**0**	**0**	**0**	**0**
5	NE	S, SW, NW	A	Roztocze Środkowe PLH060017	8.45	SW	NO	**0**	**0**	**0**	**0**
5	NE	S, SW, NW	A	Dolina Łętowni PLH060040	10.19	NW	YES	**0**	**0**	**0**	**0**
5	NE	S, SW, NW	A	Uroczyska Lasów Adamowskich PLH060094	10.55	SE	NO	**0**	**0**	**0**	**0**
5	NE	S, SW, NW	A	Kornelówka PLH060091	14.21	NE	NO	**0**	**0**	**0**	**0**
5	NE	S, SW, NW	A	Izbicki Przełom Wieprza PLH060030	14.27	N	YES	**0**	**0**	**0**	**0**
5	NE	S, SW, NW	D	Skierbieszowski Park Krajobrazowy	9.02	NE	NO	**0**	**0**	**0**	**0**
5	NE	S, SW, NW	D	Szczebrzeszyński Park Krajobrazowy	12.13	SWW	YES	**0**	**0**	**0**	**0**
5	NE	S, SW, NW	E	Roztoczański Park Narodowy	8.45	SW	NO	**0**	**0**	**0**	**0**
5	NE	S, SW, NW	F	Hubale	7.18	SE	YES	**0**	**0**	**0**	**0**
5	NE	S, SW, NW	F	Wieprzec	8.46	SE	YES	**0**	**0**	**0**	**0**
6	S	W, SW	B	Lasy Lęborskie PLB220006	5.78	E	YES	**0**	**0**	**0**	**0**
6	S	W, SW	A	Jeziora Choczewskie PLH220096	9.49	E, NE	YES	**0**	**0**	**0**	**0**
6	S	W, SW	A	Łebskie Bagna PLH220040	11.75	SW	YES	**0**	**0**	**0**	**0**
6	S	W, SW	A	Górkowski Las PLH220045	12.62	NWW	YES	**0**	**0**	**0**	**0**
6	S	W, SW	C	Choczewsko – Saliński	5.27	N–E	YES	**0**	**0**	**0**	**0**
6	S	W, SW	C	Pradoliny Redy – Łeby	5.41	S–SE	YES	**0**	**1**	**0**	**0**

TEST SITE			PROTECTED AREA					POTENTIAL IMPACT			
Test site No	GROUND WATER FLOW DIRECTION	PREDOMINANT WIND DIRECTION	RANK	NAME	DISTANCE FROM THE DRILL SITE	DIRECTION TO THE DRILL SITE	WATER-DEPENDENT ECOSYSTEMS [1)]	NOISE	TRANS-PORTATION	WATER	AIR
6	S	W, SW	C	Fragment Pradoliny Łeby i Wzgórza Morenowe	9.31	S	NO	**0**	**0**	**0**	**0**
6	S	W, SW	C	Nadmorski	14.65	N	NO	**0**	**0**	**0**	**0**
6	S	W, SW	E	Słowiński Park Narodowy – otulina	6.73	NW	YES	**0**	**0**	**0**	**0**
6	S	W, SW	F	Pużyckie Łęgi – otulina	3.94	E	YES	**0**	**0**	**0**	**0**
6	S	W, SW	F	Pużyckie Łęgi	4.02	E	YES	**0**	**0**	**0**	**0**
6	S	W, SW	F	Borkowskie Wąwozy	9.17	N	NO	**0**	**0**	**0**	**0**
6	S	W, SW	F	Długosz Królewski w Łęczynie	10.16	E	NO	**0**	**0**	**0**	**0**
6	S	W, SW	F	Nowe Wicko	10.98	NWW	YES	**0**	**0**	**0**	**0**
6	S	W, SW	F	Wielistowskie Źródliska	11.04	SE	YES	**0**	**0**	**0**	**0**
6	S	W, SW	F	Łebskie Bagno – otulina	11.55	SW	YES	**0**	**0**	**0**	**0**
6	S	W, SW	F	Wielistowskie Łęgi	11.69	SE	YES	**0**	**0**	**0**	**0**
6	S	W, SW	F	Łebskie Bagno	11.75	SW	YES	**0**	**0**	**0**	**0**
6	S	W, SW	F	Las Górkowski	12.62	NWW	YES	**0**	**0**	**0**	**0**
6	S	W, SW	F	Choczewskie Cisy	14.46	N	NO	**0**	**0**	**0**	**0**
6	S	W, SW	F	Czarne Bagno	14.80	SW	YES	**0**	**0**	**0**	**0**
7	SE	SW, SE	B	Bory Tucholskie PLB220009	11.85	S	NO	**0**	**0**	**0**	**0**
7	SE	SW, SE	B	Lasy Mirachowskie PLB220008	12.36	N	YES	**0**	**0**	**0**	**0**
7	SE	SW, SE	A	Uroczyska Pojezierza Kaszubskiego PLH220095	2.37	E, SE	YES	**0**	**1**	**0**	**0**
7	SE	SW, SE	A	Rynna Dłużnicy PLH220081	7.31	SW	NO	**0**	**0**	**0**	**0**
7	SE	SW, SE	A	Mechowiska Sulęczyńskie PLH220017	8.04	W	YES	**0**	**0**	**0**	**0**
7	SE	SW, SE	A	Dolina Słupi PLH220052	9.23	W	YES	**0**	**0**	**0**	**0**
7	SE	SW, SE	A	Nowa Sikorska Huta PLH220090	11.30	SE	NO	**0**	**0**	**0**	**0**
7	SE	SW, SE	A	Dąbrówka PLH220088	11.43	SE	NO	**0**	**0**	**0**	**0**

TEST SITE			PROTECTED AREA					POTENTIAL IMPACT			
Test site No	GROUND WATER FLOW DIRECTION	PREDOMINANT WIND DIRECTION	RANK	NAME	DISTANCE FROM THE DRILL SITE	DIRECTION TO THE DRILL SITE	WATER-DEPENDENT ECOSYSTEMS [1)]	NOISE	TRANS-PORTATION	WATER	AIR
7	SE	SW, SE	A	Jeziora Kistowskie PLH220097	11.50	NW	YES	**0**	**0**	**0**	**0**
7	SE	SW, SE	A	Jeziorka Chośnickie PLH220012	13.01	NW	YES	**0**	**0**	**0**	**0**
7	SE	SW, SE	A	Piotrowo PLH220091	14.15	SEE	NO	**0**	**0**	**0**	**0**
7	SE	SW, SE	A	Leniec nad Wierzycą PLH220073	14.87	SSE	NO	**0**	**0**	**0**	**0**
7	SE	SW, SE	A	Staniszewskie Błoto PLH220027	15.00	NNE	YES	**0**	**0**	**0**	**0**
7	SE	SW, SE	C	Gowidliński	4.48	W	YES	**0**	**1**	**0**	**0**
7	SE	SW, SE	C	Lipuski	12.10	SW	YES	**0**	**0**	**0**	**0**
7	SE	SW, SE	C	Kartuski	13.41	NEE	YES	**0**	**0**	**0**	**0**
7	SE	SW, SE	D	Kaszubski Park Krajobrazowy	1.95	E, SE	YES	**0**	**1**	**0**	**0**
7	SE	SW, SE	F	Strzelnica	11.46	SSE	NO	**0**	**0**	**0**	**0**
7	SE	SW, SE	F	Ostrzycki Las	11.54	E	YES	**0**	**0**	**0**	**0**
7	SE	SW, SE	F	Żurawie Chrusty	11.55	NE	YES	**0**	**0**	**0**	**0**
7	SE	SW, SE	F	Jeziorka Chośnickie	13.01	NWW	YES	**0**	**0**	**0**	**0**

Potential impacts on more distant areas, such as changes in water regime or permanent air pollution with gas or dust, were not found, as shown by the discussion of results from the analysed test sites.

The impacts come most frequently from transport. This suggests that when drill site is properly located with regard to environmentally valuable areas, vehicular traffic is the worst indirect nuisance that Operators should consider in their exploration projects. This conclusion is also true for residential buildings.

4.7 Drilling wastes and process fluids

Drilling wastes

The analysis was intended to establish the characteristics of the produced wastes and their potential impact on the environment. Waste characteristics are presented by two basins: the Pomeranian Basin (Lubocino, Stare Miasto, Wysin and Gapowo test sites) and the Lublin Basin (Syczyn and Zawada test sites).

The cuttings are of a dark colour with shades ranging from blackish-grey to greyish-graphite and from black and brown to russet with greyish-blue spots. Sample consistency was mainly muddy and clayish, except for Gapowo-1A well where the cuttings were mostly loose, in places micro-pellet forming. Due to these characteristics such parameters as yield point and plasticity index were not determined in these samples. Physicochemical characteristics of drilling waste solid phase are presented in the Table 4.7.

Table 4.7. Physicochemical characteristics of drilling waste solid phase

Item	Characteristics		
1	Reaction	pH	7.49–9.65
2	Water content	[%]	4.9–52.1
3	Loss on ignition *at 850^{0}C*	[%]	6.5–18.1
4	Yield point	W_P [%]	12.08–28.52*
5	Liquid limit	W_L [%]	18.95–54.69
6	Plasticity index	I_P [%]	5.74–26.17*
7	Filtration coefficient	$k = k_{10}$ [m/s]	$2.91 \cdot 10^{-8}$–$6.24 \cdot 10^{-6}$
8	Natural humidity	W_N [%]	4.9–52.1
9	Reaction	pH	7.49–9.65

* except for Gapowo-1A

The contents of inorganic constituents in solid phase of drilling wastes are presented separately for the Pomeranian and Lublin Basin (Table 4.8). Samples from the Pomeranian Basin contain more aluminium, iron, calcium, magnesium, potassium and sodium than the samples from the Lublin Basin. The contents of sulphur, total organic carbon and dissolved organic carbon, as well as chemical oxygen demand are higher in the samples from the Lublin Basin. The content of total hydrocarbons ranges from 213.79 to 1 616.14 mg/kg dw in the Pomeranian Basin and is as low as 541.03–631.72 mg/kg dw in the Lublin Basin. This, however, may reflect not only different reservoir conditions but also the type of drilling mud used (Tables 4.8 and 4.9).

Table 4.8. Contents of inorganics in the tested solid phase samples of drilling wastes from Pomeranian and Lublin Basins

Item	Composition	Composition-oxides	Pomeranian Basin	Lublin Basin	Elemental	Pomeranian Basin	Lublin Basin
			%			mg/kg dm	
1	Main components	Loss on ignition	6.5–18.11	12.66–13.1	–	65 000–18 1100	126 600–131 000
2		Al_2O_3	3.47–9.09	4.88–7.26	Al	18 370.1–48 112.7	25 824.7–38 418.3
3		Fe_2O_3	2.97–9.5	4.76–5.31	Fe	20 811.5–66 476.4	33 342.7–37 149.8
4		CaO	2.83–8.75	5.95–6.64	Ca	20 209.2–62 542.9	42 527.4–47 479.2
5		MgO	1.4–4.97	2.89–3.76	Mg	8 432.4–29 968.9	17 449.8–22 697.6
6		Na_2O	0.26–6.06	0.37–0.41	Na	1 948.4–4 4987	2 783.6–3 067.1
7		K_2O	0.82–2.68	1.18–2.02	K	6 794.4–22 247.8	9 801.1–16 762.7
8		SO_3	$1.40 \cdot 10^{-3}$–3.85	1.78–1.99	S	17.3–46 180	23 830.2–214 204
9		P_2O_5	0.11–0.27	0.2–0.24	P	473.4–1 191.9	851.6–1 051.1
10		Mn_2O_5	0.07–0.25	0.06–0.07	Mn	377.4–1 447.8	362.6–411.4
11		BaO	0.05–0.32	0.1–0.28	Ba	454.7–2 836.3	877.2–2 516.2
12	Trace components	Li_2O	$4.00 \cdot 10^{-3}$–0.01	$5.00 \cdot 10^{-3}$–$6.40 \cdot 10^{-3}$	Li	18.6–31.5	25.1–29.8
13		B_2O_3	$2.00 \cdot 10^{-4}$–0.01	$2.00 \cdot 10^{-3}$–$6.70 \cdot 10^{-3}$	B	0.5–33.1	5.0–16.9
14		ZnO	$6.70 \cdot 10^{-3}$–0.024	0.011–0.039	Zn	53.4–189.4	90.6–313.2
15		SrO	$1.00 \cdot 10^{-3}$–0.069	0.016–0.0281	Sr	87.7–582.2	136.6–237.2
16		SnO_2	$4.00 \cdot 10^{-4}$–$5.00 \cdot 10^{-3}$	$3.00 \cdot 10^{-4}$–$1.10 \cdot 10^{-3}$	Sn	3–24.7	2.5–8.5
17		TlO_2	$1.00 \cdot 10^{-4}$–$3.00 \cdot 10^{-4}$	$3.00 \cdot 10^{-4}$–$3.00 \cdot 10^{-4}$	Tl	0.1–2.3	0.2–2.5
18		As_2O_5	$3.00 \cdot 10^{-4}$–$2.30 \cdot 10^{-3}$	$1.20 \cdot 10^{-3}$–$1.40 \cdot 10^{-3}$	As	2.1–14.7	7.5–9
19		SeO_2	$2.00 \cdot 10^{-5}$–$2.60 \cdot 10^{-4}$	$1.00 \cdot 10^{-5}$–$2.50 \cdot 10^{-4}$	Se	0.1–1.8	0.1–1.8
20		MoO_3	$1.80 \cdot 10^{-5}$–$7.90 \cdot 10^{-4}$	$9.20 \cdot 10^{-4}$–$1.60 \cdot 10^{-3}$	Mo	0.2–5.2	6.1–10.9
21		CrO_3	$6.10 \cdot 10^{-3}$–0.018	$7.70 \cdot 10^{-3}$–0.012	Cr	31.8–95.4	40.1–64.2
22		CdO	$1.00 \cdot 10^{-5}$–$4{,}00 \cdot 10^{-5}$	$4.00 \cdot 10^{-5}$–6,00·10–4	Cd	0.1–0,4	0.4–5.3
23		PbO	$6{,}30 \cdot 10^{-4}$–$9{,}90 \cdot 10^{-3}$	$1{,}50 \cdot 10^{-3}$–$1{,}54 \cdot 10^{-3}$	Pb	5.8–91.5	13.5–14,3
24		CoO	$8{,}10 \cdot 10^{-4}$–$2{,}50 \cdot 10^{-3}$	$1{,}20 \cdot 10^{-3}$–$1{,}50 \cdot 10^{-3}$	Co	6.4–19.3	9.3–11,9
25		NiO	$3{,}50 \cdot 10^{-3}$–$9{,}10 \cdot 10^{-3}$	$5{,}30 \cdot 10^{-3}$–$7{,}80 \cdot 10^{-3}$	Ni	27.5–71.3	41.2–61
26		BeO	$1{,}20 \cdot 10^{-4}$–$7{,}10 \cdot 10^{-4}$	$2{,}30 \cdot 10^{-4}$–$7{,}80 \cdot 10^{-4}$	Be	0.4–2.6	0.84–2.8
27		V_2O_5	$8{,}50 \cdot 10^{-3}$–0,021	0,011–0,041	V	47.4–119.4	64.2–230.5
28		CuO	$3{,}50 \cdot 10^{-3}$–4,3	$6{,}40 \cdot 10^{-3}$–$7{,}30 \cdot 10^{-3}$	Cu	27.6–106	50.8–58.6
29		Ag_2O	0,00–$6{,}00 \cdot 10^{-5}$	$1{,}00 \cdot 10^{-5}$–$1{,}00 \cdot 10^{-5}$	Ag	0.00–0.6	0.1–0.1
30		TiO_2	$7{,}80 \cdot 10^{-4}$–0,019	$6{,}00 \cdot 10^{-3}$–$8{,}50 \cdot 10^{-3}$	Ti	4.7–114.8	36–51.1
31		HgO	0,00–$3{,}00 \cdot 10^{-5}$	$2{,}00 \cdot 10^{-5}$–$2{,}00 \cdot 10^{-5}$	Hg	0.02–0.3	0,03–0,2
32		Sb_2O_3	$1{,}40 \cdot 10^{-6}$–$1{,}20 \cdot 10^{-3}$	$1{,}00 \cdot 10^{-5}$–$1{,}00 \cdot 10^{-5}$	Sb	0.03–10	0.05–0.05
33		*UO_3	0,00–$1{,}40 \cdot 10^{-3}$	$1{,}00 \cdot 10^{-5}$–$3{,}00 \cdot 10^{-3}$	U	0.08–11.8	0.05–24.8
34					F	29–698	112–192
35					*NNH_4	37.6–267	134–155

Table 4.9. Contents of organic compounds in the tested solid phase samples of drilling wastes from Pomeranian and Lublin Basins

Item	Component		Unit	Pomeranian Basin	Lublin Basin
1	Hydrocarbons:	total	mg/kg s.m.	213,79–1 616,14	541,03–631,72
2		aliphatic	mg/kg s.m.	212,35–1 591,22	480,42–628,79
3		aromatic	mg/kg s.m.	1,08–70,18	2,93–60,62
4	Gasoline	total	mg/kg s.m.	3,25–210,53	8,84–181,85
5	Mineral oil	total	mg/kg s.m.	99,8–1541,38	359,18–622,94
6	Total organic carbon (TOC)		mg/kg s.m.	3 058–34 241	39 325–40 650
7	Dissolved organic carbon (DOC)		mg/kg s.m.	1 113–7 736	7 548–10 190
8	Phenolic index (phenols)		mg/kg s.m.	< 0,5–0,8	1,4–7
9	COD (dichromate method)		mg/kg s.m.	7 950–89 032	108 400–110 229
10	Surfactants (anionic)		mg/kg s.m.	9,0–64,6	34,30
11	Multi-ring aromatics (MRA)				
11.1	*Naphtalene*		mg/kg s.m	< 0,001–0,018	< 0,001
11.2	*Acenaphtene*			< 0,001–0,018	0,005–0,082
11.3	*Fluorene*			< 0,001–0,012	< 0,001–0,022
11.4	*Phenanthrene*			< 0,001–0,109	0,019–0,374
11.5	*Anthracene*			< 0,001–0,004	0,002–0,006
11.6	*Fluoranthene*			< 0,001–0,016	< 0,001–0,2
11.7	*Pyrene*			< 0,001–0,018	< 0,001–0,08
11.8	*Benzo(a)anthracene*			0,008–0,446	0,017–0,438
11.9	*Chrysene*			0,003–0,065	< 0,001–0,079
11.10	*Benzo(b)fluoranthene*			< 0,001–0,012	< 0,001–0,018
11.11	*Benzo(k)fluoranthene*			< 0,001–0,009	< 0,001–0,009
11.12	*Benzo(a)pyrene*			< 0,001–0,014	< 0,001–0,016
11.13	*Dibenzo(ah)anthracene*			< 0,001–0,005	< 0,001–0,009
11.14	*Benzo(ghi)perylene*			< 0,001–0,016	0,02–0,024
11.15	*Indeno(1,2,3,c,d)pyrene*			< 0,001–0,014	< 0,001–0,008

< below the limit of detection

The criteria of Economy and Labour Minister's Ordinance of 7 September 2005 *on the criteria and procedures of waste acceptance for storage at landfills intended for a particular type of waste* (2005 Journal of Laws No. 186, Item 1553, as amended), superseded by Economy Minister's Ordinance of 8 January 2013 *on the criteria and procedures of waste acceptance for storage at landfills intended for a particular type of waste* (2013 Journal of Laws No. 38) were used to assess potential environmental impact from drilling wastes and the potential for reuse of drilling wastes. Assessment results are presented in the Tables 4.10 and 4.11.

Leachability tests of the analysed drilling wastes, as made in order to establish environmental impact from the waste management by storage, revealed that the wastes would not meet eligibility criteria for storage at landfills intended for a particular type of waste only due to the parameters that are highlighted with colours in the Tables 4.10 and 4.11. In these cases, the threshold values for waste storage at landfills intended for inert wastes, non-hazardous and inert wastes and, exceptionally, for hazardous wastes have been exceeded.

Table 4.10. Solid drilling waste tests for compliance with permitted threshold leachabilty values* as a criterion for storage eligibility – the Pomeranian Basin

Item	Component	Waste storage eligibility criteria			Lubocino test site		Stare Miasto test site	Wysin test site		Gapowo test site
		Permitted value			1/OSW/1/ 07.09.2012	1/OSW/2/ 01.10.2012	2/OSW/1/ 23.08.2012	4/OSW/1/ 27.03.2013	4/OSW/2/ 26.04.2013	7/OSW/1/ 13.02.2014
		1)	2)	3)	[mg/kg dm]					
		[mg/kg dm]								
1	**Antimony (Sb)**	5	0,06	0,7	0.11	$8.33 \cdot 10^{-2}$	$6.77 \cdot 10^{-2}$	$3.8 \cdot 10^{-2}$	$2.9 \cdot 10^{-2}$	$8.6 \cdot 10^{-2}$
2	**Arsenic (As)**	25	0,5	2	$5.91 \cdot 10^{-2}$	$1.28 \cdot 10^{-2}$	$7.81 \cdot 10^{-2}$	$2.2 \cdot 10^{-2}$	$6.3 \cdot 10^{-2}$	0.13
3	**Barium (Ba)**	300	20	100	$5.72 \cdot 10^{-2}$	0.76	$1.48 \cdot 10^{-2}$	$1.4 \cdot 10^{-2}$	$7.2 \cdot 10^{-2}$	$7.7 \cdot 10^{-2}$
4	**Beryllium (Be)**	–	–	–	$4.70 \cdot 10^{-4}$	$3.09 \cdot 10^{-3}$	$4.95 \cdot 10^{-4}$	$2.8 \cdot 10^{-4}$	$1.6 \cdot 10^{-3}$	$2.6 \cdot 10^{-3}$
5	**Boron (B)**	–	–	–	$1.97 \cdot 10^{-2}$	$2.06 \cdot 10^{-2}$	$2.46 \cdot 10^{-2}$	$6.2 \cdot 10^{-2}$	$4.4 \cdot 10^{-2}$	$5.5 \cdot 10^{-2}$
6	**Chromium (Cr)**	70	0,5	10	$7.60 \cdot 10^{-4}$	$5.33 \cdot 10^{-3}$	$1.46 \cdot 10^{-3}$	$4.0 \cdot 10^{-3}$	$1.9 \cdot 10^{-3}$	$4.3 \cdot 10^{-3}$
7	**Tin (Sn)**	–	–	–	$6.63 \cdot 10^{-2}$	$1.69 \cdot 10^{-2}$	$4.70 \cdot 10^{-3}$	$5.0 \cdot 10^{-3}$	$9.3 \cdot 10^{-3}$	$3.70 \cdot 10^{-2}$
8	**Zinc (Zn)**	200	4	50	$2.56 \cdot 10^{-2}$	$5.51 \cdot 10^{-2}$	$6.11 \cdot 10^{-2}$	$4.2 \cdot 10^{-2}$	$5.6 \cdot 10^{-2}$	$8.7 \cdot 10^{-2}$
9	**Aluminium (Al)**	–	–	–	$5.85 \cdot 10^{-3}$	1.12	0.45	$7.0 \cdot 10^{-3}$	0.18	0.1
10	**Cadmium (Cd)**	5	0,04	1	$5.28 \cdot 10^{-2}$	$2.29 \cdot 10^{-3}$	$5.45 \cdot 10^{-3}$	$1.3 \cdot 10^{-3}$	$2.6 \cdot 10^{-3}$	$6.1 \cdot 10^{-3}$
11	**Cobalt (Co)**	–	–	–	$4.20 \cdot 10^{-3}$	$5.81 \cdot 10^{-3}$	$9.02 \cdot 10^{-3}$	$4.0 \cdot 10^{-3}$	$2.8 \cdot 10^{-3}$	$3.4 \cdot 10^{-3}$
12	**Manganese (Mn)**	–	–	–	$2.47 \cdot 10^{-3}$	0.34	$1.39 \cdot 10^{-3}$	$4.0 \cdot 10^{-2}$	$2.5 \cdot 10^{-3}$	$2.9 \cdot 10^{-3}$
13	**Copper (Cu)**	100	2	50	$1.50 \cdot 10^{-3}$	$1.15 \cdot 10^{-4}$	$1.44 \cdot 10^{-2}$	$3.2 \cdot 10^{-3}$	$4.6 \cdot 10^{-3}$	$1.8 \cdot 10^{-2}$
14	**Molybdenum (Mo)**	30	0,5	10	$2.92 \cdot 10^{-2}$	$1.23 \cdot 10^{-2}$	$4.29 \cdot 10^{-3}$	$7.8 \cdot 10^{-3}$	$4.1 \cdot 10^{-3}$	$8.2 \cdot 10^{-2}$
15	**Nickel (Ni)**	40	0,4	10	$4.52 \cdot 10^{-3}$	$3.47 \cdot 10^{-3}$	$7.47 \cdot 10^{-3}$	$1.0 \cdot 10^{-2}$	$1.2 \cdot 10^{-2}$	$1.2 \cdot 10^{-3}$
16	**Lead (Pb)**	50	0,5	10	$5.50 \cdot 10^{-3}$	$2.57 \cdot 10^{-2}$	$3.84 \cdot 10^{-2}$	$3.5 \cdot 10^{-2}$	$3.2 \cdot 10^{-2}$	$2.8 \cdot 10^{-2}$

Item	Component	Waste storage eligibility criteria			Lubocino test site		Stare Miasto test site	Wysin test site		Gapowo test site
		Permitted value			1/OSW/1/ 07.09.2012	1/OSW/2/ 01.10.2012	2/OSW/1/ 23.08.2012	4/OSW/1/ 27.03.2013	4/OSW/2/ 26.04.2013	7/OSW/1/ 13.02.2014
		1)	2)	3)	[mg/kg dm]					
		[mg/kg dm]								
17	**Potassium (K)**	–	–	–	17 400	1 348.8	980.4	26.8	3.2	3 846
18	**Mercury (Hg)**	2	0,01	0,2	$2.2 \cdot 10^{-5}$	$2.8 \cdot 10^{-4}$	$4.8 \cdot 10^{-4}$	$7.9 \cdot 10^{-3}$	$5.7 \cdot 10^{-3}$	$3.8 \cdot 10^{-2}$
19	**Selenium (Se)**	7	0,1	0,5	1.78	0.59	1.1	1.5	$8.7 \cdot 10^{-2}$	2.05
20	**Sodium (Na)**	–	–	–	14073	4721.2	364.6	23 585	9 465	1133
21	**Silver (Ag)**	–	–	–	$2.81 \cdot 10^{-4}$	$2.67 \cdot 10^{-3}$	$4.01 \cdot 10^{-3}$	$6.6 \cdot 10^{-3}$	$7.9 \cdot 10^{-3}$	$2.6 \cdot 10^{-3}$
22	**Strontium (Sr)**	–	–	–	$9.19 \cdot 10^{-2}$	0.34	$2.41 \cdot 10^{-2}$	$9.0 \cdot 10^{-2}$	$9.6 \cdot 10^{-2}$	0.39
23	**Thallium (Tl)**	–	–	–	$7.82 \cdot 10^{-2}$	$5.81 \cdot 10^{-2}$	$3.38 \cdot 10^{-2}$	$3.0 \cdot 10^{-2}$	$2.3 \cdot 10^{-2}$	0.11
24	**Titanium (Ti)**	–	–	–	$1.10 \cdot 10^{-4}$	$1.83 \cdot 10^{-3}$	$9.48 \cdot 10^{-4}$	$1.5 \cdot 10^{-4}$	$1.0 \cdot 10^{-3}$	$8.2 \cdot 10^{-4}$
25	**Vanadium (V)**	–	–	–	$9.08 \cdot 10^{-3}$	$3.21 \cdot 10^{-3}$	$6.77 \cdot 10^{-3}$	$8.4 \cdot 10^{-3}$	$2.2 \cdot 10^{-2}$	$1.4 \cdot 10^{-2}$
26	**Calcium (Ca)**	–	–	–	521	921.8	360.7	961.9	240.5	3206
27	**Iron (Fe)**	–	–	–	$1.41 \cdot 10^{-2}$	$3.00 \cdot 10^{-2}$	$3.57 \cdot 10^{-2}$	0.15	$5.0 \cdot 10^{-2}$	$7.0 \cdot 10^{-3}$
28	**Ammonia nitrogen(NH_4)**	–	–	–	18.1	6.8	3	2.6	18	55
29	**Bromine, bromides (Br)**	–	–	–	30.7	16.7	4.9	509	221	16.2
30	**Chlorides (Cl-)**	25 000	800	15 000	44 675.8	5 141.3	1 468.9	34 393	13 473.7	10 637.2
31	**Fluorides (F-)**	500	10	150	12	264	47.6	12.6	37.6	12.4
32	**Sulphates (SO_4^{2-})**	50 000	1000	20	51.3	158.5	465.8	230	94.2	300.1

Item	Component	Waste storage eligibility criteria			Lubocino test site		Stare Miasto test site	Wysin test site		Gapowo test site
		Permitted value			1/OSW/1/ 07.09.2012	1/OSW/2/ 01.10.2012	2/OSW/1/ 23.08.2012	4/OSW/1/ 27.03.2013	4/OSW/2/ 26.04.2013	7/OSW/1/ 13.02.2014
		1)	2)	3)	[mg/kg dm]					
		[mg/kg dm]								
33	H-carbonates (HCO_3^-)	–	–	–	1098.3	6834	3172.9	610.2	2 257.70	1952.6
	(carbonates CO_3^{2-})				(–)	(–)	(–)	(–)	(–)	(–)
34	Dissolved solids (TDS)	100 000	4 000	60 000	78 920.9	19 991.8	7 028.5	65 010	27 916	21 435
35	Phenolic index	–	1	–	< 0.02	0.25	< 0.02	0.5	≤ 0.02	< 0.01
36	Total organic carbon (TOC)		30 000		630	6880	2860	510	2 170	812
37	Dissolved organic carobon (DOC)	1 000	500	800	620	6360	2650	430	2 030	794
38	Anionic surfactants	–	–	–	< 0.2	2.8	6.4	4.9	6.9	< 0.5
39	COD	–	–	–	1080	17200	7340	1 370	5 850	2580
40	Total gasoline	–	–	–	2.52	3.1	1.94	15.5	5.7	29.4
41	Total mineral oils	–	500	–	5.97	4.08	7.87	97	66.7	6.8
42	Total hydrocarbons	–	–	–	8.49	7.19	9.81	112.5	72.4	36.2
43	Aliphatic hydrocarbons	–	–	–	7.85	6.15	9.16	107.4	70.5	26.4
44	Aromatic hydrocarbons	–	–	–	0.84	1.03	0.65	5.2	1.9	9.8

Item	Component	Waste storage eligibility criteria			Lubocino test site		Stare Miasto test site	Wysin test site		Gapowo test site
		Permitted value			1/OSW/1/ 07.09.2012	1/OSW/2/ 01.10.2012	2/OSW/1/ 23.08.2012	4/OSW/1/ 27.03.2013	4/OSW/2/ 26.04.2013	7/OSW/1/ 13.02.2014
		1)	2)	3)	[mg/kg dm]					
		[mg/kg dm]								
45	**Multi-ring aromatic hydrocarbons (MAH)**	–								
	Naphtalene	–	–	–	$< 10^{-5}$	0.007	$< 10^{-5}$	$9 \cdot 10^{-5}$	$< 10^{-5}$	$8.8 \cdot 10^{-3}$
	Acenaphthene	–	–	–	$8.7 \cdot 10^{-4}$	$< 10^{-5}$	$< 10^{-5}$	$< 10^{-5}$	$< 10^{-5}$	$< 10^{-5}$
	Fluorene	–	–	–	$< 10^{-5}$	$8.8 \cdot 10^{-4}$	$7.8 \cdot 10^{-4}$	$< 10^{-5}$	$< 10^{-5}$	$3.8 \cdot 10^{-4}$
	Phenanthrene	–	–	–	$1.8 \cdot 10^{-4}$	$8.5 \cdot 10^{-4}$	2.0·10–4	$< 10^{-5}$	$< 10^{-5}$	$2.8 \cdot 10^{-3}$
	Anthracene	–	–	–	$< 10^{-5}$	$< 10^{-5}$	$< 10^{-5}$	$< 10^{-5}$	$< 10^{-5}$	$2.6 \cdot 10^{-4}$
	Fluoranthene	–	–	–	$1.8 \cdot 10^{-4}$	$4.1 \cdot 10^{-4}$	$3.7 \cdot 10^{-4}$	$< 10^{-5}$	$< 10^{-5}$	$5.2 \cdot 10^{-4}$
	Pyrene	–	–	–	$4.2 \cdot 10^{-4}$	$4.9 \cdot 10^{-4}$	$5.6 \cdot 10^{-4}$	$5 \cdot 10^{-4}$	$< 10^{-5}$	$2.0 \cdot 10^{-4}$
	Benzo(a)anthracene	–	–	–	$8.5 \cdot 10^{-4}$	0.001	0.001	$5 \cdot 10^{-5}$	$< 10^{-5}$	$1.6 \cdot 10^{-4}$
	Chrysene	–	–	–	$4.1 \cdot 10^{-4}$	$4.4 \cdot 10^{-4}$	$4.5 \cdot 10^{-4}$	$< 10^{-5}$	$< 10^{-5}$	$< 10^{-5}$
	Benzo(b)fluoranthene	–	–	–	$2.9 \cdot 10^{-4}$	$2.9 \cdot 10^{-4}$	$3.5 \cdot 10^{-4}$	$< 10^{-5}$	$< 10^{-5}$	$< 10^{-5}$
	Benzo(k)fluoranthene	–	–	–	$2.3 \cdot 10^{-4}$	$2.3 \cdot 10^{-4}$	$2.1 \cdot 10^{-4}$	$< 10^{-5}$	$< 10^{-5}$	$< 10^{-5}$
	Benzo(a)pyrene	–	–	–	2.40	$1.7 \cdot 10^{-4}$	$1.2 \cdot 10^{-4}$	$< 10^{-5}$	$< 10^{-5}$	$< 10^{-5}$
	Dibenzo(ah)anthracene	–	–	–	$9 \cdot 10^{-5}$	$1.2 \cdot 10^{-4}$	$1.2 \cdot 10^{-4}$	$< 10^{-5}$	$< 10^{-5}$	$< 10^{-5}$
	Benzo(ghi)perylene	–	–	–	$1.9 \cdot 10^{-4}$	$1.4 \cdot 10^{-4}$	0.012	$< 10^{-5}$	$< 10^{-5}$	$< 10^{-6}$
	Indeno(1,2,3,c,d)pyrene	–	–	–	$2.2 \cdot 10^{-4}$	$< 10^{-4}$	$< 10^{-4}$	$< 10^{-4}$	$< 10^{-4}$	$< 10^{-6}$

Item	Component	Waste storage eligibility criteria			Lubocino test site		Stare Miasto test site	Wysin test site		Gapowo test site
		Permitted value			1/OSW/1/ 07.09.2012	1/OSW/2/ 01.10.2012	2/OSW/1/ 23.08.2012	4/OSW/1/ 27.03.2013	4/OSW/2/ 26.04.2013	7/OSW/1/ 13.02.2014
		1)	2)	3)	[mg/kg dm]					
		[mg/kg dm]								
46	Reaction–pH	–	–	–	pH					
					7.68	7.9	7.65	7.49	7.88	8.43
47	Specific conductivity [mS/cm]	–	–	–	mS/cm					
					142.8	5 600	15.6	109	49.6	36.4
48	Acid neutralisation capacity (ANC)	(pH =7)	–	–	[mgCaCO3/kg s.m.]					
					900	5 600	2678	10	37	1 600

Explanation:
* according to basic test
1) hazardous wastes, 2) inert wastes, 3) non-hazardous waste and inert waste
< below the limit of detection

exceedance of the value permitted for hazardous, non-hazardous waste and inert waste
exceedance of the value permitted for non-hazardous waste and inert waste
exceedance of the value permitted for inert wastes

Table 4.11. Solid drilling waste tests for compliance with permitted threshold leachability values* as a criterion for storage eligibility – the Lublin Basin

Item	Component	Waste storage eligibility criteria			Syczyn test site	Zawada test site
		Permitted value			3/OSW/1/23.10.2012	5/OSW/1/06.02.2013
		1)	2)	3)	[mg/kg dm]	
		[mg/kg dm]				
1	**Antimony (Sb)**	5	0.06	0.7	$4.20 \cdot 10^{-2}$	$6.1 \cdot 10^{-2}$
2	**Arsenic (As)**	25	0.5	2	$4.64 \cdot 10^{-2}$	$5.9 \cdot 10^{-2}$
3	**Barium (Ba)**	300	20	100	$7.49 \cdot 10^{-2}$	$3.4 \cdot 10^{-2}$
4	**Beryllium (Be)**	–	–	–	$6.56 \cdot 10^{-4}$	$8.5 \cdot 10^{-4}$
5	**Boron (B)**	–	–	–	$2.53 \cdot 10^{-2}$	$4.0 \cdot 10^{-2}$
6	**Chromium (Cr)**	70	0.5	10	$2.88 \cdot 10^{-3}$	$3.4 \cdot 10^{-3}$
7	**Tin (Sn)**	–	–	–	$2.56 \cdot 10^{-3}$	$1.0 \cdot 10^{-2}$
8	**Zinc (Zn)**	200	4	50	$3.49 \cdot 10^{-2}$	$4.5 \cdot 10^{-2}$
9	**Aluminium (Al)**	–	–	–	0.56	0.53
10	**Cadmium (Cd)**	5	0.04	1	$5.90 \cdot 10^{-3}$	$8.6 \cdot 10^{-4}$
11	**Cobalt (Co)**	–	–	–	$1.20 \cdot 10^{-2}$	$4.7 \cdot 10^{-3}$
12	**Manganese (Mn)**	–	–	–	$5.54 \cdot 10^{-3}$	$2.8 \cdot 10^{-3}$
13	**Copper (Cu)**	100	2	50	$1.00 \cdot 10^{-3}$	$7.4 \cdot 10^{-3}$
14	**Molybdenum (Mo)**	30	0.5	10	$7.70 \cdot 10^{-3}$	$9.8 \cdot 10^{-3}$
15	**Nickel (Ni)**	40	0.4	10	$7.25 \cdot 10^{-3}$	$2.6 \cdot 10^{-3}$
16	**Lead (Pb)**	50	0.5	10	$2.08 \cdot 10^{-2}$	$3.4 \cdot 10^{-2}$
17	**Potassium (K)**	–	–	–	2179.3	189
18	**Mercury (Hg)**	2	0.01	0.2	$< 10^{-6}$	$4.6 \cdot 10^{-2}$
19	**Selenium (Se)**	7	0.1	0.5	1.41	1.6
20	**Sodium (Na)**	–	–	–	692.1	1 431.8
21	**Silver (Ag)**	–	–	–	$2.73 \cdot 10^{-3}$	$3.1 \cdot 10^{-3}$
22	**Strontium (Sr)**	–	–	–	0.12	$8.1 \cdot 10^{-2}$
23	**Thallium (Tl)**	–	–	–	$1.81 \cdot 10^{-2}$	$4.4 \cdot 10^{-2}$
24	**Titanium (Ti)**	–	–	–	$5.36 \cdot 10^{-4}$	$3.6 \cdot 10^{-3}$
25	**Vanadium (V)**	–	–	–	$5.02 \cdot 10^{-2}$	$9.3 \cdot 10^{-3}$
26	**Calcium (Ca)**	–	–	–	280.6	200.4
27	**Iron (Fe)**	–	–	–	$8.68 \cdot 10^{-2}$	0.14
28	**Ammonia nitrogen(NH_4)**	–	–	–	< 0.25	7.2
29	**Bromine, bromides (Br)**	–	–	–	2.2	6.7
30	**Chlorides (Cl-)**	25 000	800	15 000	1 418.1	1 418.3
31	**Fluorides (F-)**	500	10	150	10.1	58.4
32	**Sulphates (SO_4^{2-})**	50 000	1 000	20 000	123.9	18.6
33	**H-carbonates (HCO_3^-)**	–	–	–	2 745.8	959.3
	(carbonates CO_3^{2-})				601.1	661.8

Item	Component	Waste storage eligibility criteria			Syczyn test site	Zawada test site
		Permitted value			3/OSW/1/23.10.2012	5/OSW/1/06.02.2013
		1)	2)	3)	[mg/kg dm]	
		[mg/kg dm]				
34	**Dissolved solids (TDS)**	100 000	4 000	60 000	8 309.5	5 305.7
35	**Phenolic index**	–	1	–	1.7	0.2
36	**Total organic carbon (TOC)**		30 000		9 380	6 370
37	**Dissolved organic carobon (DOC)**	1 000	500	800	7 280	5 780
38	**Anionic surfactants**	–	–	–	4.2	8.4
39	**COD**	–	–	–	24 400	18 180
40	**Total gasoline**	–	–	–	8.78	18.21
41	**Total mineral oils**	–	500	–	235.98	184.4
42	**Total hydrocarbons**	–	–	–	244.82	202.6
43	**Aliphatic hydrocarbons**	–	–	–	241.87	196.5
44	**Aromatic hydrocarbons**	–	–	–		
45	**Multi-ring aromatic hydrocarbons (MAH)**	–				
	Naphtalene	–	–	–	0.012	$< 10^{-5}$
	Acenaphthene	–	–	–	$< 10^{-5}$	$< 10^{-5}$
	Fluorene	–	–	–	0.002	$< 10^{-5}$
	Phenanthrene	–	–	–	0.001	$< 10^{-5}$
	Anthracene	–	–	–	$3.0 \cdot 10^{-5}$	$6.0 \cdot 10^{-5}$
	Fluoranthene	–	–	–	$7.8 \cdot 10^{-4}$	$< 10^{-5}$
	Pyrene	–	–	–	$6.9 \cdot 10^{-4}$	$< 10^{-5}$
	Benzo(a)anthracene	–	–	–	0.002	$< 10^{-5}$
	Chrysene	–	–	–	$5.2 \cdot 10^{-4}$	$< 10^{-5}$
	Benzo(b)fluoranthene	–	–	–	$2.9 \cdot 10^{-4}$	$< 10^{-5}$
	Benzo(k)fluoranthene	–	–	–	$2.5 \cdot 10^{-4}$	$< 10^{-5}$
	Benzo(a)pyrene	–	–	–	$1.8 \cdot 10^{-4}$	$< 10^{-5}$
	Dibenzo(ah)anthracene	–	–	–	10^{-3}	$< 10^{-5}$
	Benzo(ghi)perylene	–	–	–	$1.3 \cdot 10^{-4}$	$< 10^{-5}$
	Indeno(1,2,3,c,d)pyrene	–	–	–	$< 10^{-4}$	$< 10^{-4}$
46	**Reaction–pH**	–	–	–	**pH**	
					8.55	9.65
47	**Specific conductivity [mS/cm]**	–	–	–	**mS/cm**	
					11.3	7.68
48	**Zdolność (ANC) do neutralizacji kwasów**	*(pH = 7)*	–	–	**[mg$CaCO_3$/kgs.m^{-1}]**	
					3 750	73

Explanation as in Table 4.10

The contents of chlorides, fluorides, dissolved solids, dissolved organic carbon and selenium in drilling wastes from both from both Pomeranian and Lublin Basin exceed the permitted concentrations for storage at facilities intended for inert wastes and non-hazardous waste and inert waste.

In the Pomeranian Basin, contents of dissolved organic carbon and chlorides were higher than those permitted for storage at facilities intended for hazardous wastes.

Moreover, in some of the cuttings samples the following indices were found to be higher than the eligibility thresholds for waste storage at facilities intended for inert wastes:

- antimony, cadmium and mercury in the Pomeranian Basin:

and

- antimony, mercury and phenolic index in the Lublin Basin.

This comparison was made at the testing stage solely for the purposes of establishing waste characteristics in terms of potential environmental impact from waste management by storage; under existing regulations, it is permitted to store extractive wastes only in extractive waste management facilities, according to the Act of 10 July 2008 *on extractive wastes* – 2008 Journal of Laws No. 138, Item 865, as amended). With January 2015, under the amended Geological and Mining Law, inert and non-hazardous and inert extractive wastes are permitted for storage in underground storage facilities.

As a general rule, all of the tested drilling wastes were toxic to test organisms, but the level of toxicity tended to decrease with increasing dilution of samples. Accordingly, the substances toxic to selected test organisms are not permanently associated with the solid waste matrix (rock clasts in this particular case) and are readily extractable.

Process fluids

Like in the case of drilling wastes, the analysis of process fluids applied in hydraulic fracture stimulation for potential environmental risks is presented separately for the two basins: the Pomeranian Basin (Lubocino, Stare Miasto and Gapowo test sites) and the Lublin Basin (Syczyn and Zawada test sites). The Wysin test site was not included in the analysis due a change in Operator's strategy (hydraulic fracture stimulation was cancelled at this test site).

Flowback fluid chemistry is highly variable in terms of both quality and quantity. The contents of particular elements are contingent on both fracturing fluid composition and the fracture stimulated rock medium. Much higher concentrations of some elements comparing with fracturing fluid may indicate that they pass to the process fluid as a result of contact with the rock (Tables 4.12 and 4.13).

Table 4.12. Flowback fluid concentrations of elements leached out from fractured formations in the Pomeranian Basin

Element	Lubocino	Stare Miasto	Gapowo
	mg/l		
1	2	3	4
boron (B)	$5.82 \cdot 10^{-3}$–0.49	–	–
barium (Ba)	$1.28 \cdot 10^{-3}$–1.76	$1.36 \cdot 10^{-2}$	2.91–15.95
calcium (Ca)	0.23–199.56	10.17	18.56–48.46
cesium (Cs)	$1.61 \cdot 10^{-3}$–17.5	$4.6 \cdot 10^{-2}$	0–20.79
potassium (K)	12.42–86.68	3.28	–
sodium (Na)	0.84–601.65	22.14	83.95–187.09
selenium (Se)	$4.19 \cdot 10^{-2}$–0.61	0.30	2.7–40.58
strontium (Sr)	$8.80 \cdot 10^{-4}$–13.22	1.56	3.44–17.3

1	2	3	4
silver (Ag)	–	–	$1.13 \cdot 10^{-2}$–$3.04 \cdot 10^{-2}$
aluminum (Al)	–	2.36	$1.52 \cdot 10^{-2}$–$3.67 \cdot 10^{-2}$
arsenic (As)	$5.52 \cdot 10^{-3}$–0.13	–	0.14–1.1
cadmium (Cd)	–	–	$7.7 \cdot 10^{-3}$–$1.2 \cdot 10^{-2}$
sulphur (S)	–	2.76	1.29–120.36

– an increased concentration not found

Table 4.13. Flowback fluid concentrations of elements leached out from fractured formations in the Lublin Basin

Element	**Syczyn**	**Zawada**
	mg/l	
boron (B)	$9.04 \cdot 10^{-2}$–0.6	$3.36 \cdot 10^{-2}$–0.35
barium (Ba)	0.14–0.46	2.02–59.50
calcium (Ca)	8.30–36.97	2.64–28.43
cesium (Cs)	0.11–1.32	0.17 –54.57
potassium (K)	1.67–13.16	–
lithium (Li)	$8.03 \cdot 10^{-2}$–0.22	$5.66 \cdot 10^{-5}$–0.60
magnesium (Mg)	0.93–3.39	–
sodium (Na)	54.34–173.53	16.72–304.63
strontium (Sr)	1.12–5.56	0.56 –23.45
aluminum (Al)	–	$3.00 \cdot 10^{-3}$–$3.06 \cdot 10^{-2}$
cadmium (Cd)	–	$1.94 \cdot 10^{-4}$–$3.64 \cdot 10^{-3}$
cobalt (Co)	–	$6.16 \cdot 10^{-4}$–$3.01 \cdot 10^{-3}$
iron (Fe)	$2.54 \cdot 10^{-2}$–$7.06 \cdot 10^{-2}$	$5.27 \cdot 10^{-3}$–1.34
titanium (Ti)	–	$5.97 \cdot 10^{-5}$–$3.66 \cdot 10^{-4}$
uranium (U)	–	$1.69 \cdot 10^{-3}$–$1.93 \cdot 10^{-2}$
yttrium (Y)	–	$8.18 \cdot 10^{-5}$–$1.93 \cdot 10^{-4}$
zinc (Zn)	–	$6.79 \cdot 10^{-4}$–$2.02 \cdot 10^{-2}$

– an increased concentration not found

Flowback fluids are highly variable in terms of organic compound content. The differences were found not only between test sites but also between particular fluid batches from the same well (Table 4.14). All of the tested fluids were found to be toxic to test organisms, Therefore, untreated fluids should be never released to the environment, even accidentally, for example in an emergency. All available steps should be taken to ensure that flowback fluids are reused on the site in subsequent operations. Hauling to other drilling locations or extractive waste management facilities should always follow waste transport procedures. A proper management/treatment of process fluids will ensure safety to the population and to the environment.

Table 4.14. Contents of organic components in the tested fracturing and flowback fluids in the Pomeranian and Lublin Basins

Item	Component	Unit	Fracturing fluids	Flowback fluids	Fracturing fluids	Flowback fluids
			Pomeranian Basin		Lublin Basin	
1	Total hydrocarbons	mg/dm³	1.73–424.956	0.49–427.21	40.94–263.97	6.73–146.31
2	Aliphatic hydrocarbons	mg/dm³	1.70–420.486	0.46–418.08	40.36–258.14	4.64–134.98
3	Aromatic hydrocarbons	mg/dm³	0.03–4.47	0.02–18.68	0.58–9.37	0.86–11.85
4	Total gasoline	mg/dm³	0.10–13.409	0.04–56.06	1.75–28.12	2.57–35.54
5	Total mineral oil	mg/dm³	1.63–411.547	0.42–331.97	39.19–246.48	0.45–112.32
6	Total organic carbon (TOC)	mg/dm³	724–2 093	115–1090	399–828	131–853
7	Dissolved organic carbon (DOC)	mg/dm³	604–2 011	99–919	384–2 188	105–1193
8	Phenolic index (phenols)	mg/dm³	0.03–0.04	0.02–0.79	0.03–1.25	0.02–1.20
9	COD (dichromate methods)	mg/dm³	1 920–5 360	307–6 230	1 303–6840	554–5 920
10	(anionic) surfactants	mg/dm³	0.30–0.70	0.68–25.66	0.50–25.82	0.50–16.0
11	Multi-ring aromatics (MRA)					
11.1	*Naftalen*	mg/dm³	$1.9\cdot10^{-5}$–$4.36\cdot10^{-4}$	$<5\cdot10^{-6}$–$2.86\cdot10^{-4}$	$<5\cdot10^{-6}$–$1.7\cdot10^{-4}$	$1.0\cdot10^{-5}$–$6.5\cdot10^{-4}$
11.2	*Acenaften*		$3.5\cdot10^{-5}$–$2.38\cdot10^{-4}$	$6\cdot10^{-5}$–$1.38\cdot10^{-4}$	$<5\cdot10^{-6}$	$<5\cdot10^{-6}$–$3.2\cdot10^{-4}$
11.3	*Fluoren*		$5.6\cdot10^{-5}$–$6.8\cdot10^{-5}$	$<5\cdot10^{-6}$–$4.6\cdot10^{-5}$	$<5\cdot10^{-6}$–$2.1\cdot10^{-5}$	$<5\cdot10^{-6}$–$2.6\cdot10^{-4}$
11.4	*Fenantren*		$4.4\cdot10^{-5}$–$1.67\cdot10^{-4}$	$4.3\cdot10^{-5}$–$2.31\cdot10^{-4}$	$<5\cdot10^{-6}$	$1.1\cdot10^{-5}$–$1.35\cdot10^{-4}$
11.5	*Antracen*		$<5\cdot10^{-6}$–$3.3\cdot10^{-5}$	$1.9\cdot10^{-5}$–$8.79\cdot10^{-5}$	$<5\cdot10^{-6}$	$<5\cdot10^{-6}$–$5.6\cdot10^{-5}$
11.6	*Fluoranten*		$1.2\cdot10^{-5}$–$1.4\cdot10^{-5}$	$<5\cdot10^{-6}$–$1.46\cdot10^{-4}$	$<5\cdot10^{-6}$	$<5\cdot10^{-6}$–$1\cdot10^{-4}$
11.7	*Piren*		$<5\cdot10^{-6}$–$3.6\cdot10^{-5}$	$2.4\cdot10^{-5}$–$1.16\cdot10^{-4}$	$<5\cdot10^{-6}$	$<5\cdot10^{-6}$–$5.4\cdot10^{-5}$
11.8	*Benzo(a)antracen*		$<5\cdot10^{-6}$–$8.5\cdot10^{-5}$	$<5\cdot10^{-6}$–$3.82\cdot10^{-4}$	$<5\cdot10^{-6}$–$1.2\cdot10^{-4}$	$<5\cdot10^{-6}$–$4.3\cdot10^{-5}$
11.9	*Chryzen*		$<5\cdot10^{-6}$–$2.9\cdot10^{-5}$	10^{-4}–$8.7\cdot10^{-5}$	$<5\cdot10^{-6}$–$8\cdot10^{-6}$	$<5\cdot10$–6
11.10	*Benzo(b) fluoranten*		$<5\cdot10^{-6}$–$2.0\cdot10^{-5}$	$<5\cdot10^{-6}$–$3.6\cdot10^{-5}$	$<5\cdot10^{-6}$	$<5\cdot10^{-6}$–$1.0\cdot10^{-4}$
11.11	*Benzo(k) fluoranten*		$<5\cdot10^{-6}$–$8\cdot10^{-6}$	$<5\cdot10^{-6}$–$2.0\cdot10^{-5}$	$<5\cdot10^{-6}$	$<5\cdot10^{-6}$
11.12	*Benzo(a)piren*		$<5\cdot10^{-6}$–$1.9\cdot10$–^{5}	$<5\cdot10^{-6}$–$6.1\cdot10^{-5}$	$<5\cdot10^{-6}$	$<5\cdot10^{-6}$
11.13	*Dibenzo(ah) antracen*		$<5\cdot10^{-6}$–$5\cdot10^{-6}$	$<5\cdot10^{-6}$–10^{-5}	$<5\cdot10^{-6}$	$<5\cdot10^{-6}$–$<10^{-5}$
11.14	*Benzo(ghi) perylen*		$<5\cdot10^{-6}$–$1.6\cdot10^{-5}$	$<5\cdot10^{-6}$–$3.3\cdot10^{-5}$	$<5\cdot10^{-6}$	$<5\cdot10^{-6}$–$2.1\cdot10^{-4}$
11.15	*Indeno(1,2,3,c,d) piren*		$<1\cdot10^{-5}$	$<1\cdot10^{-5}$	$<1\cdot10^{-5}$	$<1\cdot10^{-5}$

< below the limit of detection

Concentration of natural radioactive isotopes

The tests for concentration of natural radioactive isotopes were made to assess potential impact of drilling wastes (cuttings), spent mud, process fluids and solid flowback wastes on the environment and human health, but also to identify the potential for management of the produced wastes in processes other than neutralisation. Considering the importance of radiological protection of the population and of the environment, the results and the discussion thereof are presented in a separate chapter.

The assessment was made according to Council of Ministers' Ordinance of 2 January 2007 *on the requirements concerning the contents of radioactive isotopes in buildings intended for occupation by people or livestock, on industrial wastes used in construction industry and on control of contents of these isotopes* (2007 Journal of Laws No. 4, Item 29). In line with this Ordinance, activity indicators may not exceed by more than 20% the following values:

- $f_1 = 1$ and $f_2 = 200$ Bq/kg, for raw and construction materials used in buildings that are intended for occupation by people or living stock,
- $f_1 = 2$ and $f_2 = 400$ Bq/kg, for industrial wastes used in erected structures constructed in build-up areas or areas designated for building-up under local planning and zoning scheme, or used for levelling such areas,
- $f_1 = 3.5$ and $f_2 = 1000$ Bq/kg, for industrial wastes used in substructures of erected buildings other than specified above and for levelling of areas other than specified above,
- $f_1 = 7$ and $f_2 = 2000$ Bq/kg, for wastes used in substructures of erected buildings or in underground facilities, including railway and road tunnels, except for industrial wastes used in mine workings.

Moreover, if the material is permitted for use as hydraulic proppant, the specific activity of radium (^{226}Ra + ^{228}Ra) should not exceed 10 000 Bq/kg.

According to United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), world's average content of radioactive isotopes in soil is equal to: ^{40}K – 412, ^{226}Ra – 32 and ^{228}Th – 45 [Bq/kg]. It should be noted that this is average content, while in some soils the natural activity may be even several fold higher.

Average contents of radioactive isotopes in Earth's crust are about: ^{40}K – 650, ^{226}Ra – 30 and ^{228}Th – 40 [Bq/kg]. However, the content of these elements in Earth's crust is strongly dependent on the type of the rocks and ranges:

- from several to approx. 2 000 Bq/kg in the case of ^{40}K,
- from several to approx. 150 Bq/kg in the case of ^{226}Ra (several hundred Bq/kg in crude oil reservoir rocks),
- from several to several hundred Bq/kg in the case of ^{228}Th.

The analysis of the impact of spent mud and drilling wastes on the environment and human health revealed that ^{40}K and ^{226}Ra concentrations are slightly higher than world's average for the soils, but still within the natural range of variability.

The activities of natural radionuclides in waste samples have been compared to the natural radioactivity of soils to demonstrate that the exposure from waste handling is similar to natural exposure. Radionuclide activities in the tested samples are comparable to Earth crust activity. A slightly above average, but still within the environmental range, ^{40}K activity in drilling wastes (from 1092 to 446 Bq/kg in Pomeranian Basin wastes and from 918 to 739 in wastes from the Lublin Basin) derives probably from mud contact with a rock having slightly above average concentration of ^{40}K or mud preparation with substances containing ^{40}K-enriched potassium.

The concentrations of ^{226}Ra and ^{228}Th were low in the tested samples and consistent with average natural concentrations in the environment. The f_1 and f_2 indices, as determined for the tested drilling wastes and spent mud, comply with the requirements set for building materials applied in buildings intended for occupation by people and living stock, as specified in the Council of Ministers' Ordinance of 2 January 2007 *on the requirements concerning the contents of radioactive isotopes in buildings intended for occupation by people or livestock, on industrial wastes used in construction industry and on control of contents of these isotopes* (2007 Journal of Laws No. 4, Item 29). The f_1 and f_2 activity indices did not exceed 1 and 200 Bq/kg, respectively. Spent mud from Lubocino-2H is the only exception with f_1 index equal to 1.33±0.07 due to a higher concentration of ^{40}K.

The contents of natural radioactive isotopes in fracturing fluids were low, consistent with natural concentrations in the environment and amounted to:

- for ^{40}K : from 18±6 to 196±19 Bq/kg (in the Pomeranian Basin) and from <10 to 79±12 Bq/kg (in the Lublin Basin, except for one sample with ^{40}K content equal to 447 Bq/kg);
- for ^{226}Ra and ^{228}Th: <10 Bq/kg, both in Pomeranian and Lublin Basin.

Concentrations of natural isotopes in flowback fluids were slightly higher than in fracturing fluids, but generally still within natural concentration ranges in the environment:

for ^{40}K : from 51±11 to 347±20 Bq/kg (Pomeranian Basin) and from 12±7 to 492±35 Bq/kg (Lublin Basin);

- for ^{226}Ra : from <10 to 48±4 Bq/kg (Pomeranian Basin) and from 19±3 to 29±3Bq/kg (Lublin Basin);
- for ^{228}Th: from <10 to 21±3 Bq/kg (Pomeranian Basin) and < 10 Bq/kg (Lublin Basin).

Concentrations of radioactive ^{226}Ra and ^{228}Th isotopes in the tested flowback proppants were several fold higher than the UNSCEAR average for soil (in both Pomeranian and Lublin Basins), but the proppants are still suitable for use in construction industry, for example in the substructures of erected buildings and in underground structures.

Concluding, all drilling wastes and spent mud meet the requirements of Council of Ministers' Ordinance of 2 January 2007 *on the requirements concerning the contents of radioactive isotopes in buildings intended for occupation by people or livestock*…. .

Considering the content of natural radioactive isotopes, the tested wastes are suitable, from the radiological point of view, for use in production of building materials, in land levelling and for road building. In should be noted, however, that if wastes that comply with the f_1 and f_2 indices are used for land levelling, construction of roads and sports/recreational facilities, the dose absorbed 1 m above the ground, road or facility may not exceed 0.3 mGy/h (an additional layer of other material should be placed to ensure compliance with that requirement). Moreover, the wastes can be used as an admixture to hydraulic proppant. Considering the consistency, however, only solid drilling wastes (cuttings) and probably proppant are suitable for reusing them in these applications.

5. Recommendations for Delivery of Environmental Monitoring

In addition to the definition of the purpose, the identification of the scope and frequency of testing is a precondition for successful delivery of monitoring operations. Adequate testing methodology (justification of the selected sampling points, choosing adequate limits of determination and detection, sensitivity, uncertainty and precision of the determinations) must be considered. Economic reasonableness of the adopted testing scope and frequency is the third monitoring factor to be considered.

The following recommendations apply to the monitoring of processes and operations that are associated with prospection and exploration of unconventional hydrocarbons, as well as to the monitoring of the status of particular environmental compartments. They are based on the results of tests made under this Project, other similar undertakings and on extensive professional experience held by the authors.

5.1 Terrain deformations

Project impact on the terrain can be considered in the context of two categories:

- terrain deformations that arise directly from Operator's works, mainly construction ones; and
- terrain deformations and ground stability compromised by hydraulic fracturing-induced seismic events.

Terrain deformations caused directly by drill site operations, mainly construction works, involve in this particular case site levelling, topsoil piling in embankments and construction of earthen tanks. The local geography and related diversity of landforms in the drill site area are the key factors that control the extent of deformations. The drill sites included in this study were located mostly in little diversified flat areas. Only Lubocino drill site was located at the slope of a small elevation, with related runoff and shallow groundwater problems. Terrain deformations from site levelling and construction of earthen structures at the drill site are temporary and reversible. The rank of and nuisance from that impact is small, the changes are observable and associated with the analysed operations, although they are not specific, i.e. are typical to other projects as well. Monitoring of these operations is not necessary. It is recommended to locate drill sites in the plains. Moreover, site reclamation designs should foresee initial status restoration, also in terms of terrain, e.g. by spreading the soil piled in embankments, removal of tanks and restoring natural sloping of the terrain.

Based on the effected surveys it is concluded that terrain monitoring, for example with 3D scanning techniques, is superfluous in the exiting unconventional gas and oil exploration areas. However, should in the future exploration and production operations enter areas with a more complicated terrain, especially those at risk of surficial mass movements, monitoring of slope stability at the site of operations and near access roads should be unreservedly required. In that case the application of 3D terrain scanning, combined with traditional earth slide monitoring techniques, will provide initial status data for subsequent use as reference for measurements made throughout and after the operations, and will enable delivery of control measurements wherever traditional monitoring of mass movements is impracticable or economically non-viable.

Potential changes in morphology and ground stability compromised by hydraulic fracturing-induced seismic events is the second category of terrain impact. No impacts of this kind were found based on the following studies:

- a dedicated seismic monitoring delivered by Polish Academy of Sciences at Łebień test site and by Chief Mining Institute at Syczyn and Zawada test sites;
- analysis of data from micro-seismic monitoring delivered by the Operators at Lubocino and Stare Miasto test sites;
- an assessment of the effects of potential events by terrain monitoring with high resolution terrestrial laser scanning (LiDAR) at Stare Miasto test site.

Micro-seismic tests are made by the Operators as part of field development operations, but it would be advisable to deliver test data to competent authorities (mining offices, geological survey) for an environmental safety-oriented interpretation.

Poland is a non-seismic area, but permanent seismic monitoring should be considered in the areas of intensive exploration and production with horizontal drilling and hydraulic fracture stimulation operations. In addition to ensuring safety by enabling early detection of potential stress field instability, the project of this kind would have scientific merits by providing methodology and analytical inputs to the European debate on environmental impact from these operations. Above all, it would address the concerns of the public opinion that requests safety of exploration, also in terms of potential induced seismic events.

5.2 Noise

The level of noise generated by shale gas exploration is highly variable, depending on particular stages of drill site operations. Therefore, the scope and frequencies of sound measurements should be first of all adapted to Operators' schedules of work.

Directive 2002/49/EC states that "environmental noise means unwanted or harmful outdoor sound created by human activities, including noise emitted by means of transport, road traffic, rail traffic, air traffic, and from sites of industrial activity". Noise levels are measured to assess the nuisance to the local residents. The extent of nuisance to the residents is contingent on the following three factors: the degree of the permitted sound level exceedance, time of exposure and the number of residents exposed to the noise. The perceived nuisance may differ from one individual to another and lead to several misunderstandings that frequently have consequences at law.

In order to be able to interpret noise impact from a drill site, the baseline status (i.e. the level of noise prevailing before the beginning of Operator's work) must be first established so as to enable an assessment of actual impact of Operator's activities on the acoustic environment. Exceedances reported from the studies were of a short duration and most often derived from operation of generator sets and pumps at hydraulic fracture stimulation. In order to establish the level of environment pollution with noise, it is recommended to monitor on a continuous basis the most annoying operations, i.e. those that involve the highest pollution of the environment with noise.

The effected studies have shown that noise should be monitored wherever a drill site is located in immediate neighbourhood (less than 500 m) of residential buildings. If the distance to the nearest residential buildings is less than 500 m, noise should be monitored in two points:

- at the drill site, and
- at the exposed, usually the nearest houses.

A monitoring delivered this way facilitates interpretation and adds credibility to the measurements that should be made with digital sound analysers holding valid calibration certificates. The regulatory environmental noise assessment criteria are specified in Environment Minister's Ordinance *on the permitted noise levels in the environment* (Journal of Laws No. 120 of 14 June 2007, Item 826, as amended). The measurements are intended to determine the indices of noise that are applied to establish and control the environment use conditions in a period of 24 hours:

- **equivalent daytime sound level $L_{Aeq\,D}$** applies to 8 consecutive least favourable daytime hours,
- **equivalent night-time sound level $L_{Aeq\,N}$** applies to 1 least favourable night-time hour.

Difficulties with differentiating between drill site impact and the impact of vehicular traffic on the sound level was a problem encountered at monitoring operations. In order to assess the scale of the problem, additional measurements were made at Gapowo test site. The results have clearly demonstrated that the results are likely to be scrambled, if measurements are made in immediate proximity of roads. The noise generated by vehicular traffic on a nearby road heavily affected the level of sound and the exceedances. This observation highlights the importance of baseline measurements made before the beginning of drill site operations (at the site of the planned works and at the nearest residential buildings).

Noise measurements should be made, as far as possible, in adequate weather conditions (temperature above –5°C, no rain or snowfall and strong wind). The results will serve as the basis for an assessment of the impact of Operator's activity on the acoustic environment and of nuisances to the local communities. Moreover, they will constitute factual evidence at any potential litigation.

5.3 Ambient air

In light of tests made, drilling unconventional oil and gas wells, including hydraulic fracture stimulation, does not involve a serious risk to the environment and population. Although concentrations of such gases as sulphur dioxide, nitrogen oxides, volatile organic compounds (C_2–C_{12}) or BTEX compounds increase during operation of high-performance combustion engines, only occasionally they exceed the standards or recommendations. Since the operations are normally delivered in open space and are of a short duration, potential effects are unlikely to remain on completion of works.

Handling a loose material, such as proppant of which huge volumes are used in hydraulic fracture stimulation, may involve dusting problems. Handling operations themselves are of a short duration, but considering high volumes and, consequently, a significant number of deliveries it is recommended to apply handling arrangements that prevent dusting. These may include deliveries in closed containers emptied within collective silos or use of screens or protective sleeves.

Accordingly, a continuous air monitoring is not required during the operations. The decision on whether to install industrial monitoring should be at the discretion of the drill site Operator.

Greenhouse gas emissions from unconventional oil and gas exploration are a more serious problem, in terms of both local and global safety. Since methane – the main constituent of natural gas – is an important greenhouse gas, it is vital to control its emissions at exploration, appraisal and production of natural gas. Available experience demonstrates that methane escapes to the atmosphere from flowback fluid tanks and through the flare, if flammable gas concentrations are too low for ignition.

Other potential methane emission sources are gas-flow tests and compromised well integrity (e.g. cement bond failure). In the latter case, emissions may occur over a long period of time. The intensity of methane emissions is contingent on the equipment used during and after well stimulation. The application of increasingly advanced technical solutions, including two- and three-stage separators, flare gas burning and after burning small volumes of gas in closed combustion units, help to minimize the emissions. However, all of these installations have their boundary conditions of operation, e.g. gas separators will not work if gas concentration is too low; similarly, a certain minimum flammable gas concentration is required to sustain the flame at the flare. If these conditions are not met, reservoir gas escapes to the atmosphere. It is extremely difficult to measure the volume of such emissions and estimates bear a higher or lower degree of uncertainty. So far, the emission of this kind has not been estimated in Poland so its significance is unknown.

The foregoing demonstrates how difficult it is to monitor total methane emission at well drilling and stimulation stages. Nevertheless, changes in atmospheric methane concentrations should be monitored in order to ensure that the operations are properly delivered. An emission of methane detected near the well may indicate inappropriate well completion, in particular casing and cementation failures.

Drill site operators are expected to monitor gas content in flowback fluids, as increased concentrations may indicate a failure of separators and a higher methane emission from flowback fluid tanks.

Moreover, in accordance with HSE standards operators should monitor permanently methane concentrations in potential methane leakage points, such as flowback fluid outlets to the tanks, as well as in rooms where people congregate. In practice, such measurements are not intended to measure actual concentrations of methane. Instead, they are to check whether the concentration is getting close to the explosive limit above which it represents a risk to the people and drill site facilities.

On the other hand, it is the task of the scientific engineering team to develop a method for measuring methane emissions at well stimulation and gas-flow testing stages. Only the measurement of actually emitted methane will permit to answer the question whether the emissions represent a significant contribution to the global greenhouse gas emission and whether the green completion measures applied are adequate. Moreover, the development of a method for measuring total emissions from a particular area will enable monitoring of abandoned drill sites for upward gas migration to the ground surface along the abandoned wells.

It is much easier to monitor gas emissions at the stage of production, when the well is protected with a Christmas tree and the gas is delivered via a sealed system to storage tanks or to the grid. Several methods are available for such measurements that are made along gas transmission pipes and at potential leakage spots.

HI Flow Sampler (http://www.bacharach-inc.com/hi-flow-sampler.htm), that directly measures the rate of gas leakage from industrial facilities, is the key method developed in the 1990's .

Tests made using this method allows for gas leakage estimation with 10% accuracy. The sampler is intended for measuring the rate of gas leakage at a variety of pipelines, valve shields and sealing, compressors used in gas transmission and storage and compressor facilities. Leakage rate is estimated by sampling at a very high flow rate (0.08 to 12 m^3/h), so as to capture total gas leaking from the tested facility. Hi Flow Sampler measures with precision flow rates of the samples and natural gas concentrations for estimation of gas leakage rate with an accuracy of up to 10%.

Leakage estimation based on isotopic tests of selected air components is another available method (David, Allen et al., 2013). However, due to several limitations estimation error may be as high as 100% which makes this method hardly applicable.

5.4 The soil

Considering theoretically possible reservoir gas migration along the string of exploratory well casing, it is proposed to monitor on a long-term basis soil gas concentrations of methane in the near-well zone at each test site. The tests should be made in the near-well zone, around each borehole in a layout of three lines extending radially every 120° from the well. If more wells have been drilled from a single pad, the lines extending from neighbouring wells should be merged.

It is proposed to collect samples at the well and at distance of 1, 5, 10 and 30 m. The tests should be made at least every 2 years counting from completion of hydraulic fracture stimulation or well abandonment, using the same testing techniques, in comparable weather conditions. It is recommended to avoid testing in the winter season.

If a significant increase in concentration is reported, an extended identification of isotopes should be performed in order to confirm potential gas migration along the casing string.

5.5 Surface and ground waters

The scope and frequency of monitoring of the aquatic environment (surface and ground waters) in shale gas exploration, appraisal and potentially production areas in Poland should be first of all adapted to the concession operators' planned scope and schedule of works. Therefore, it is vital to possess a thorough knowledge of the planned operations and related process characteristics. Another important factor is the investigation of the approach to site protection, including the storm water drainage system. Site management and protection arrangements are controlled by process operations, but should also reflect local conditions in the drill site area. Accordingly, it is equally important to consider geology, hydrogeological conditions and the hydrographic network in the area of operations (Fig. 5.1).

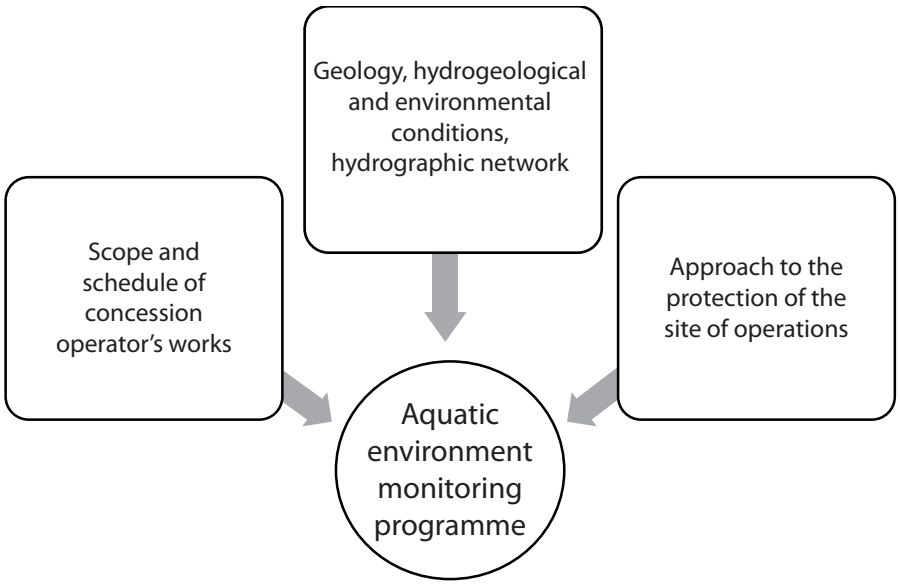


Fig. 5.1. Aquatic environment monitoring factors.

Considering a high variability of geology and hydrogeological conditions in Poland, these factors must be each time analysed for any drilling location. Some of the key factors to be considered at environmental monitoring planning stage are:

- the number of aquifers/water-bearing levels and their interrelations (hydraulic contact, sealing packages),
- aquifer stratigraphy and medium type (porous, fractured, karstic),
- the depth to the top aquifer,
- the depth to the main commercial aquifer (the source of potable water supply to the population),
- the type of groundwater table (confined/unconfined),
- isolation from the ground surface (type and thickness of poorly permeable rocks),
- groundwater flow direction,
- the distance from the nearest water course (or lake, drainage ditch, if applicable) and water course type (draining/infiltrating),
- maximum depth of freshwater aquifers (or active water exchange zone, if applicable),
- depth to mineralized waters in the basement,
- presence of fault zones in the basement,
- sealing packages below the freshwater aquifers.
- It is recommended to develop a monitoring programme that addresses local and regional aspects of the aquifer system. The local system should include points for monitoring of the top aquifer, in order to identify any potential anthropogenic pressures on the groundwater, mainly from ground surface activities. Depending on actual needs of the local system monitoring, piezometers should be installed in immediate drill site neighbourhood, upstream and downstream in the direction of flow. The regional network analysis should include the layout of commercial aquifer in the region, regional and intermediate circulation systems and, if justified (unconfined poorly isolated aquifers), the presence of protected areas, water-dependent ecosystems and large municipal water intakes.

Monitoring of aquatic environment in the areas of shale gas exploration and/or production should enable an assessment of the actual drill site impact on the surface and ground waters. To this end, the baseline (initial) status must be established to serve as a reference for the determination of any potential changes in the aquatic environment from the operations or production activities (Fig. 5.2). It should be noted that the existing land use patterns must be identified at this stage. If monitoring is started at the stage of drill site operations, the history of these operations must be first established. Otherwise, it will be much more difficult to interpret the results and their credibility will suffer. In this history context, it is important to locate places of serious failures involving emission of pollutants to the environment.

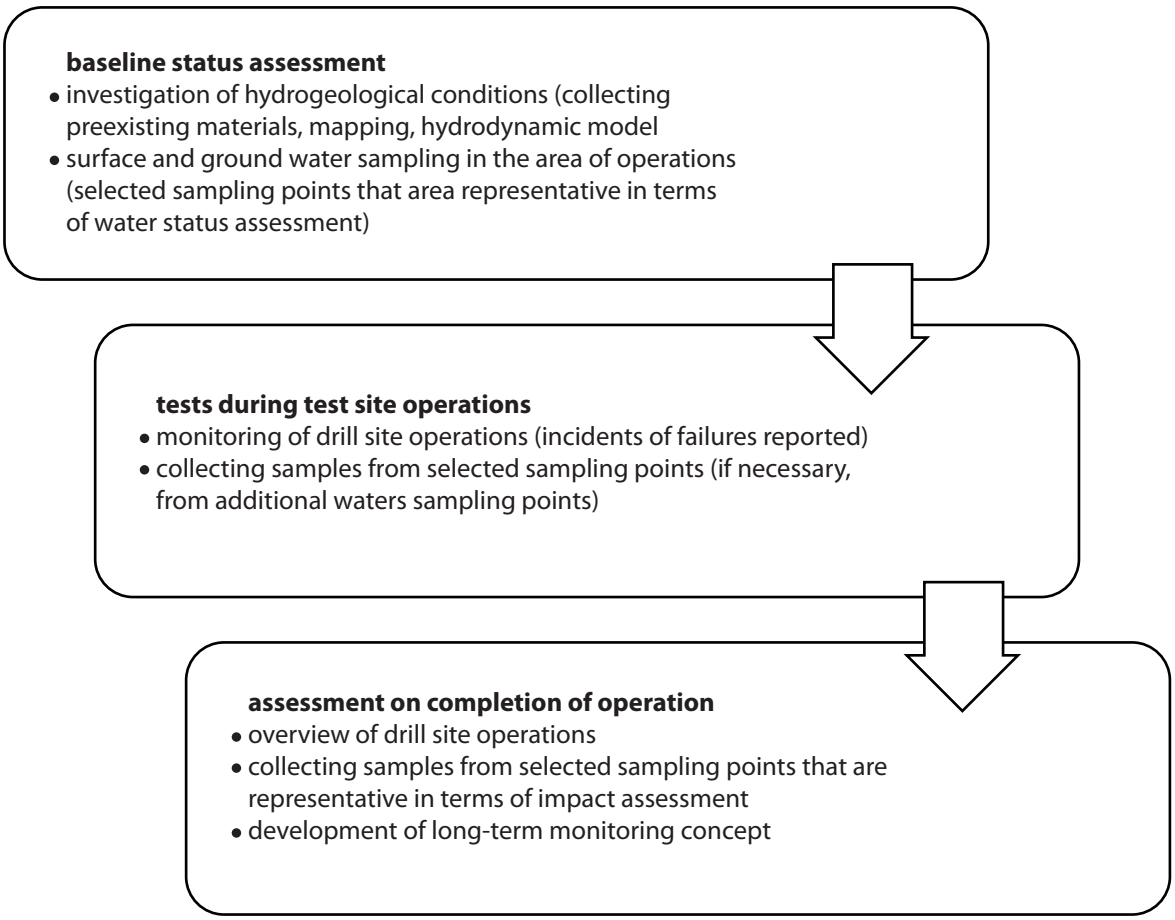


Fig. 5.2. Monitoring of aquatic environment in shale gas exploration and/or production areas.

The determination of the **baseline status** should include an investigation of hydrogeological and hydrogeochemical conditions in the planned area of operations (based on pre-existing materials and databases, including cartographic studies). Hydrogeological mapping of the planned drilling area, including identification of potential sampling facilities and groundwater table measurements, is the next stage. The identified hydrogeological facilities (hand-dug and drilled water wells, sources) should be evaluated in terms of potential for collecting representative samples for physicochemical tests (technical condition and accessibility of wells, their current use and owner's consent). The next step is to prepare a hydrodynamic model that represents hydrogeological conditions prevailing in the planned work area. By defining groundwater flow rates and directions, model studies enable the determination of the pathways for migration of potential pollutants in the aquifer. Although the model based on a schematic representation of the local geology is always a simplified image of the actual hydrogeological conditions, it allows for simulation of the range and time of the migration of pollutants. Model studies should be the basis for selection of water sampling points and, in the case of long-term monitoring, for the determination of the sampling frequency.

The tests made during drill site operations (drilling, fracturing, gas-flow testing, etc.) should be adjusted to their delivery. Updates on the progress of works and in particular information about any drilling failures or spills on the ground surface are of the essence. The latter may include any events associated with transportation and storage of chemicals, process fluids, materials handling and gas delivery. Any events of this kind should be followed by a model-based analysis of the potential for surface and ground water pollution, followed by water sampling in the indicated area. If sampling points are not available, a test well should be planned and drilled in order to sample the water (considering the local geology and hydrogeological conditions).

Monitoring tests conducted on production launching and/or completion of geological works should be based on the knowledge of hydrogeological and hydrographic conditions, considering the

results of model studies (seepage time, water flow rate and direction in the aquifer). At this stage it is recommended to select points that are located in the existing/ abandoned drill site or in its immediate neighbourhood. It is recommended to select 1–2 points (as practicable) located at the inflow of the groundwater to the test site and 2–4 points in the water outflow direction. Sampling frequency should be established considering the calculated time of water seepage through the zone of aeration and the estimates of flow flow rate in the aquifer. This workflow was adopted in this project. The Table 5.1 shows the key parameters yielded by model studies which served as the basis for the development of monitoring programme for each of the analysed test sites.

Table 5.1. Results of model studies made at each test site for monitoring programme development

Test site	Lubocino	Stare Miasto	Syczyn	Wysin	Zawada	Łebień	Gapowo
Time of water seepage through the zone of aeration (to the top aquifer)	Several months	2–3 months (approx. 70 days)	3–4 months (approx. 107 days)	approx. 4 years	approx. 2 years	approx. 3 years	approx. 7 years
Total estimated time (vertical and horizontal components) of pollutant flow from the drill site to the nearest intake/ water course/ lake	10 years to the nearest hand-dug well, 30 years to the nearest water source	3 years to Dzierzgonka River	20 years to the nearest water intake, 10 years to Świnka River	6 years to Wietcisa River	25 years to the nearest water intake, 15 years to Łabuńka River	5.5 years to the nearest water intake, 8.7 years to Kisewska Struga River	40 years to Raduńskie Górne Lake

When formulating the recommendations for aquatic environment monitoring in shale gas exploration/production areas it is important to specify the scope of testing (the determinations of the water quality indices). In this context, special attention should be paid to the co-occurrence of several aspects that should be considered at the determination of the scope of a long-term monitoring:

- potential presence of process fluids (fracturing and flowback fluids) in the environment,
- potential occurrence of fracturing effects – penetration of gas from unconventional accumulations to the environment,
- natural and/or anthropogenic pressure-altered chemistry of water in commercial aquifers.

The indices included in a medium or long-term monitoring programme should:

- be easily determinable,
- occur in the environment at relatively low concentrations,
- allow for straightforward tracking of their source.

Adding artificial indices with specific properties to the fracturing fluid should be considered in the future so as to enable the tracking of the contamination range and nature using marker methods.

The water from aquifers located in the drill site region are primarily used in hydraulic fracture stimulation operations. Therefore, inorganic and organic parameters of the water in specific aquifers and the surface waters should be considered when monitoring potential drill site impact in the future.

Fracturing fluid is a mixture of natural ground or surface water, chemical substances or preparations and proppant. The share of water additives normally does not exceed 5% of the total fracturing fluid volume. Fracturing fluids used by particular operators are highly variable in terms of physicochemical parameters.

A considerable increase in concentrations of metals, including strontium, barium, lithium, calcium and magnesium, was found in flowback fluids. In extreme cases, the concentrations were higher by four orders of magnitude comparing with fracturing fluids.

An analysis of inorganic components of fracturing and flowback fluids should consider environmental aspects of their effects. Should both process fluid penetrate to the aquifer, their chemical properties may trigger several hydrogeochemical processes, of which the most important in quantitative terms are: dissolution and precipitation of minerals in the aquifer and transitional intensification of ion exchange processes. Another issue is the role of bacteria developing in process and reservoir fluids and the intensity of casing corrosion. Corrosion dynamics depends on such factors as the contents of unassociated oxygen, pH, aggressive carbon dioxide and the concentrations of chloride and calcium ions. Moreover, SEC in the excess of 3 mS/cm intensifies corrosion processes.

By comparing the concentrations of particular process fluid indices, as determined in all test sites, it is possible to identify a group of parameters that may indicate penetration of process (fracturing and flowback) fluids to the aquifers and the products of their potential migration following hydraulic fracture stimulation. These include:

- inorganic parameters: specific electrolytic conductivity (SEC), reaction (pH), sodium, potassium, calcium, boron, lithium, strontium, barium and chlorides,
- organic parameters: phenolic index and BTEX,
- gases: methane, carbon dioxide and ethane.

The above organic and inorganic parameters, which occur in process fluids at concentrations several thousand fold higher than in natural groundwaters, are excellent indicators of pollution in the aquatic environment. Due to elevated contents, even on potential mixing with aquifer waters the concentrations will be locally higher at regular monitoring points. A marked growth trend will be detected in concentrations of these indices in the monitoring network, even if small volumes of process fluids are mixed in the stream of the water.

Based on Environment Minister's Ordinance of 21 November 2013 on the amendment of the Ordinance *on the form of and approach to monitoring of uniform parts of surface and ground water bodies* (2013 Journal of Laws, Item 1558), the following scope of measurements is proposed for test points selected according to the methodology presented in the first section of this chapter:

- water table measurement;
- collecting a water sample to be tested for physicochemical parameters of ground and surface waters.

Physicochemical tests should be made by an accredited chemical laboratory. Samples should be collected for chemical tests according to Polish standards or to the method of reference, as proposed by Environment Minister's Ordinance of 21 November 2013 (2013 Journal of Laws Item 1558). Available groundwater sampling standards are:

- PN-EN 5667-1:2007. Part 1: Guidance on the design of sampling programmes and and sampling.
- PN-EN ISO 5667-3:2005. Part 3: Guidance on preservation and handling of samples.
- PN-ISO 5667-11:2004. Part 11: Guidance on groundwater sampling.
- PN-ISO 5667-14:2004. Part 14: Guidance on quality assurance and quality control of environmental water sampling and handling.
- PN-ISO 5667-18:2004. Part 18: Guidance on sampling of groundwater at contaminated sites.
- ISO 5667-20:2007. Part 20: Guidance on the use of sampling data for decision making – Compliance with thresholds and classification systems.

Prior to sampling, water sampling points should be pumped so as to allow for at least 3 fold water exchange in the facility, remove any stagnant water and ensure that the collected sample is representative of the aquifer. Water samples should be on-the-site tested at sampling for the following parameters: water temperature, pH, specific electrolytic conductivity (SEC), redox potential and oxygen content. Water samples to be tested for cations (especially of metals) should be filtered using a membrane filter ϕ 0,45 μm and preserved with acid (or according to the procedure required by the relevant laboratory). Water samples should be properly protected and as soon as possible delivered to the accredited laboratory. Water samples should be collected using equipment and materials (pumps, sample containers, water preservation reagents, filters) that enable proper collection of samples and do interfere with water chemistry.

The proposed scope of long-term monitoring for organic and inorgani c components is presented in the Table 5.2. The set of tests is based on typical for water monitoring indices of pollutants that may penetrate to the environment at the stages of well drilling, fracture stimulation, production, abandonment and at potential failures.

Table 5.2. Tests recommended for ground and surface water monitoring

Parameter	Unit
General parameters	
Reaction pH	
Specific electrolytic conductivity (SEC)	mS/cm
Total alkalinity	mval/l
Inorganic indices	
Barium	mg/l
Boron	mg/l
Chlorides	mg/l
Lithium	mg/l
Potassium	mg/l
Sodium	mg/l
Strontium	mg/l
Calcium	mg/l
Inorganic indices	
Volatile aromatic hydrocarbons (BTEX) – benzene, toluene, ethylobenzene, o-xylene, (m+p)–xylene, total xylenes	mg/l
Phenolic index	mg/l
Gases	
Aggressive carbon dioxide	mg/l
Methane	mg/l

Reaction (pH) – a pH test allows for the determination of the potential directions of the physicochemical processes in natural and anthropogenically altered waters. The knowledge of hydrogen ions' activity allows for estimation, based on readily available in the literature stability diagrams, of the form in which a given chemical compound will migrate in a specific environment. Accordingly, the environment's potential for the formation of toxic compounds can be approximately estimated without any additional tests. Therefore, pH is sometimes used as an index of the probability of occurrence of toxic substances in the water. The groundwater natural background is 6.5–9.5 pH units (Witczak et al., 2013).

Specific electrolytic conductivity – is an easily determinable index of mineral content of the water. Due to simplicity and extremely low cost of determination, conductivity is a good indicator of the content of substances dissolved in the monitored water solutions. The groundwater natural background ranges from 0.2 to 0.7 mS/cm. In flowback fluids, SEC > 100 mS/cm.

Total alkalinity – jointly with the content of chloride ions and pH of the water total alkalinity helps to assess corrosive action of the water on the materials used. The determinations of the total alkalinity provide a wealth of information on the type of equilibrium prevailing in the aquifer (silica, carbonate, ion exchange). The groundwater natural background ranges from 1 to 6 mval/l. A high total alkalinity may indicate drilling mud and cement residues, as well as a high rate of carbonate dissolution in the groundwater. In that case the total alkalinity in combination with other parameters may suggest migration of residual process fluids in the aquatic environment.

Barium – the natural background for the groundwater is equal to 0.01–0.03 mg/l. Barium can be considered as an indicator of the occurrence of sulphate-free water with a high mineral content in the environment. Elevated barium concentration in commercial aquifers may indicate potential as-

cension of deeper waters commingling with the water of commercial aquifers. As barium tends to concentrate in clay shales, fracturing stimulation may result in occurrence of significant amounts of barium in the groundwater (if well integrity is compromised). At drilling stage, barium content in the groundwater may increase, if barite was used in heavy mud formulations.

Boron – the natural background for the groundwater ranges from 0.01 to 0.5 mg/l. Line barium, boron may indicate commercial aquifer contact with mineral waters. Unlike barium, however, boron is not used in drilling mud formulations. High boron concentrations are characteristic of biolithes: in the coals its concentrations reach 75 ppm. Concentrations as high as 49.5 mg/l were found in process fluid samples, while boron concentrations in a Quaternary aquifer di not exceed 0.05 mg/l. Considering highly contrasting concentrations in the water and process fluids, boron may be used as an index of environment contamination with process fluids.

As boron is easily absorbed by clay minerals and organic matter, a local increase in boron concentration around the well may indicate upward migration of water from deeper aquifers.

Chlorides – the natural background for the groundwater ranges from 2 to 60 mg/l. Due to very high concentrations in process fluids, especially in flowback fluids (up to 79 000 mg/l), as well as easy and fast migration in the environment, chlorides are an ideal indicator of the arrival of the first wave of potential pollutants. As a general rule, a majority of organic parameters, that potentially have a much more significant effect on the aquatic environment, migrates at a much lower rate in the groundwater. Therefore, chloride ions with retardation factor R = 1 seem to be an ideal index. High concentrations of chlorides in the water may derive from natural (geogenic) and anthropogenic sources (potentially from process fluid residues). An concentration increase in commercial aquifer by 1–2 g/l should be attributed to anthropogenic pressure from the ground surface, while concentrations in process fluids and potential drill site failure events indicate a much higher threshold of chloride ion occurrence in the groundwater.

Lithium – like boron and barium, lithium may occur at higher concentrations in a strongly mineralized groundwater. Therefore, lithium concentrations in excess of approx. 0.8 mg/l can be interpreted as an indication of commingling of deeper and shallower aquifers. Since lithium is readily adsorbed by clay minerals and organic matter, fracture stimulation may markedly intensify ion exchange processes and migration of lithium from shales into the flowback fluid, especially if a fracturing fluid with high concentrations of ammonia ions is used.

Potassium – the natural background for the groundwater ranges from 0.5 to 10.0 mg/l. Sodium and potassium may indicate a disturbance of natural processes in the groundwater. For natural conditions typical for Quaternary formations, the K:Na ratio is most often assumed as 1:10. Na and K concentrations shown in the Table 5.2 clearly depart from that general rule, mainly due to the application of NaCl-based fracturing fluid. Although potassium is a good indicator of anthropogenic pollution from farming activities, but its concentration are never that high. Furthermore, abnormally high concentrations are associated with occurrence of highly mineralized deep waters. Potassium concentrations reported from fracturing fluids are several fold higher than the hydrogeochemical background, even in carbonate aquifers of south Poland.

Sodium – the natural background for the groundwater ranges from 1 to 60 mg/l. Sodium and potassium may indicate a disturbance of natural processes in the groundwater. An increase in sodium concentrations at hydraulic fracturing processes may result from sodium desorption from clay minerals contained in the shales. Sodium content in deep aquifers may rise to as much as 150 g/l (Witczak et al., 2013). Accordingly, higher concentrations in commercial aquifers may indicate occurrence of process fluids in the aquatic environment of migration of water from deeper aquifers. A local pollution near the borehole may be attributed to fracturing fluid preparation. Such incidental events should coincide with a decrease in Ca^{+2} ion concentration in the waters and related decrease in water hardness. Due to ubiquitous occurrence of sodium the identification of the origin of higher concentrations may seem to be problematic, but by correlating them with the content of boron, calcium and chlorides it is possible to establish the origin with a relatively high degree of certainty. Therefore, it is recommended to apply sodium alongside potassium as an inorganic index in water monitoring.

Strontium – is an inorganic parameter that displays the highest contrast between fracturing fluid and flowback fluid concentration (Table 5.2). Higher concentrations are attributed to strontium desorption from intra-layer spaces of clay minerals. In naturally occurring waters, the calcium to strontium

ratio is in excess of 200. The ratio is highly variable in flowback fluids and ranges from approx. 3 to almost 20, i.e. is higher than in seawater. In brine water from Polish Lowlands strontium concentrations do not exceed 149 mg/l (at Świnoujście). The determination of the strontium content and strontium to calcium ion ratio will be a conclusive index of deep water migration in a monitoring programme.

Calcium – the natural background for the groundwater ranges from 2 to 200 mg/l. Calcium is an ubiquitous component of groundwater. Its determination in monitoring programmes is easy and comes at a low cost. In case of a typical groundwater, due to prevalent carbonate equilibrium it is easy to track its migration in the water and, by the same, establish the reasons behind abnormal concentrations. Only in exceptional cases, in waters low in sulphates, the content of calcium ions may exceed 1 g/l. In the tested locations higher calcium concentrations are associated with Na^+ ion exchange. As a monitoring index it complements interpretation of strontium, carbon dioxide and pH.

BTEX – a natural background has not been established for the groundwater, insofar as BTEX occur only under specific conditions in the environment. BTEX presence in the groundwater indicates anthropogenic impacts. There are no credible studies on the range of BTEX concentrations in unconventional gas accumulations. Top concentration in flowback fluid was 0.316 mg/l BTEX. Volatile hydrocarbons contained in oil-derived substances tend to disappear in shallow aquifers by oxidation to the zone of aeration and to the atmosphere (Witczak et al., 2013).

Phenolic index – the natural background for the groundwater ranges from 0.0 to 0.001 mg/l. Phenolic index denotes a group of aromatic hydrocarbons wherein the hydroxyl group is joined to the carbon atom of the aromatic ring. Plant phenols include flavonoids, phenolic acids, hydrolysable and condensed tannins. Plant phenols are the products of reactions that occur in metabolic processes. Due to determination difficulties and both natural and anthropogenic origin, the interpretation of phenol content is problematic. Considering, however, that the contents of anthropogenic phenols are in the order of several g/l, i.e. by 3 orders of magnitude higher than those of natural ones, the phenolic index may serve as a useful indicator of anthropogenic pressure in a groundwater monitoring programme.

Methane – as the main component of natural gas, methane is an obligatorily tested index in unconventional gas exploration, appraisal and production projects. Considering its low solubility in water, very fast oxidation by the action of oxygen, sulphate ions and bacteria, a higher methane concentration is usually interpreted as an indication of the occurrence of hydrodynamic stagnation zones or of migration from deep tectonic structures.

Aggressive carbon dioxide – the natural background for the groundwater ranges from 0.0 to 4.0 mg/l. Monitoring of aggressive carbon dioxide will enable the determination of the carbonate equilibrium status of the groundwater and, consequently, to assess whether calcium ions present in the water are associated solely with hydrogeochemical processes in the aquifers. At the same time the determination of the aggressive CO_2 content will enable an evaluation of water aggressiveness and corrosivity.

Groundwater monitoring is first of all intended to identify potential sources of pollution. Previous flowback fluid studies have demonstrated that monitoring delivered according to the above programme is fully capable of identifying the reasons behind potential pollution/contamination, while the set of parameters recommended for determination makes it possible to tell apart the ground surface-based anthropogenic pressure from drilling and fracturing operations.

6 Recommendations

6.1 Noise and living conditions in the drill site area

Two factors have an effect on the noise from unconventional gas exploration, namely:

- a heavier vehicular traffic, and
- drill site operations, including drilling and fracture stimulation (lasting in total from several weeks to a few months).

Noise emissions from vehicular transportation occur at all stages of work: from the beginning of drill site development, through drilling and fracturing operations, to well abandonment and site reclamation inclusive. A heavier vehicular transportation occurs intermittently and is limited to short periods of time, at delivery of equipment and materials that are required at particular stages of operations. A heavier vehicular traffic affects localities located near drill site access roads and its range of noise emission is wider that of the drill site. The noise from heavier vehicular traffic may also affect localities that are located at access roads several kilometres away of the drill sites. The noise from vehicular traffic directly associated with drill site operations is a short-time nuisance. It is extremely difficult to estimate the added discomfort of the noise from these transportation activities that is superposed on the traffic noise emitted independently of drill site operations.

At the drill site, the main sources of noise are Diesel engines, generator sets, mud pumps and shale shakers. The noise is clearly perceptible in immediate drill site vicinity. The operations, drilling in particular, are delivered on a round-the-clock basis (24 hours a day) over periods of time that may range from several weeks to a few months. If the drill site is located at a short distance from the nearest residential areas, the noise may represent a nuisance to the residents.

Noise propagation in the environment is highly contingent on current weather conditions (wind is the most important noise propagation factor), terrain and sound screens. The effected studies have demonstrated that drill sites located in farmland do not pose a risk of high noise emission. On the other hand, the risk of noise occurs if residential areas are located in drill site neighbourhood. Acoustic nuisances can be significantly reduced by selecting drill site locations as far as possible from buildings and using natural terrain barriers.

Well soundproofed units must be applied, if the operations are carried out in residentially-developed areas, along with screening of other drill site units and installations (Macuda, Łukańko, 2008). If the drill site is located in immediate neighbourhood of residential buildings, acoustic screens must be installed around the drill site to minimize noise emissions to the environment. Embankments of topsoil removed from the drill site have an effect similar to acoustic screens, but such barriers are effective at a short distance from the source of noise. Approx. 200 m away from drilling rigs the sound propagation pattern tends to be circular. According to studies by Macuda (2010), average ranges of the 45 dB (permitted night-time $L_{Aeq\,N}$) contour line are found at a distance of approx. 420–440 m from the drill site. Momentary noise from hydraulic fracture stimulation operations may be much higher than the drilling noise. Therefore, the distance from the nearest residential buildings should be at least 450–500 m, if hydraulic fracture stimulation is planned at the drill site.

Dust from deliveries to the drill site may be controlled by access road paving and/or sprinkling, as well as by applying coordinated delivery schedules and speed limits.

6.2 Water management

The purpose of the recommendations is to provide concession operators with guidance on delivery of operations so as to minimize effectively the risk of adverse effects on the status of surface and ground waters. Water management recommendations address the following shale gas exploration and/or appraisal issues:

- to minimize the risk of top aquifer and surface water pollution by ground surface operations,

- to minimize the risk of deeper aquifer pollution by underground drilling operations (the vertical well),
- to minimize impacts on the quantitative status of waters (protection of surface and ground waters).

An analysis of these issues should consider the fact that shale gas production stage will be much different from prospection and exploration stage, as currently implemented in Poland. The differences arise from project scale rather than technology applied, but the former aspect is particularly important in terms of water management. This is especially true for quantitative aspects.

A comprehensive approach to shale gas exploration and/or appraisal must include the definition of internal water management factors that are controlled directly by the technology applied and of external water management impacts from drill site operations (Fig. 6.1). As far as highly decisive for process efficiency and safety internal factors are considered, it is imperative to determine the requirements for water at each stage of the project, including water requirements for particular purposes. A water circulation system that enables monitoring in terms of quantity and quality will promote rational use of water. External impacts are understood as the determination of the potential effect on the safe yield and potential risk of water pollution risk in the area of operations that may adversely affect the reserves of water available to the industry and for other, frequently overriding, ends. This is also true for long-term impacts which, in a broader sense, affect the status of surface and ground waters (as defined by Framework Water Directive). Good planning for internal exploration/appraisal factors, considering the local hydrogeological and hydrographic conditions, is a precondition for safe delivery of extraction operations and effective control of the identified environmental risks. Moreover, monitoring of aquatic environment in the area of operations (delivered according to the recommendations presented in Chapter 5.5) is a key element in the evaluation of the effectiveness of measures that have been applied to mitigate the risk of water pollution.

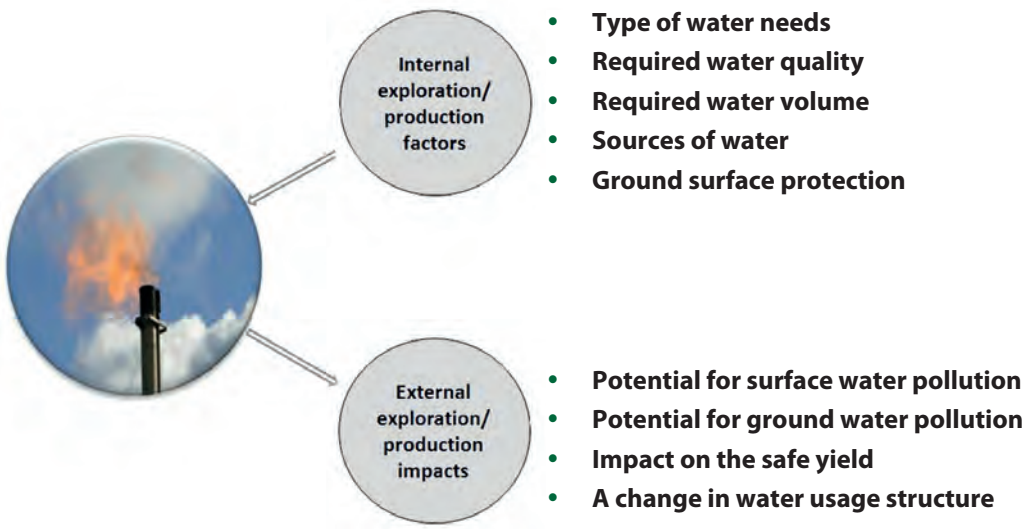


Fig. 6.1. Internal shale gas exploration and/or production factors and their external impact in the aspect of water management.

In the case of shallow aquifers (top aquifer, usually unconfined, without isolation from the ground surface), the most important thing in terms of pollution risk control is to protect the ground surface properly. In order to minimize the potential for penetration of pollutants from ground surface to the aquifers, the following measures are recommended:

- a thorough investigation of hydrogeological conditions in the planned drill site area (prior to drill site development),
- taking the inventory of protected facilities/areas in the area of potential drill site impacts that are important for the protection of ground and surface waters (protected areas, water-dependent ecosystems, groundwater drainage zones, groundwater intakes,
- development of water monitoring programme, selection and preparation of monitoring points,

- status assessment before the commencement of works,
- site levelling and paving (e.g. with concrete slabs),
- sealing the area of operations (the so-called dirty area), for example by lining it with sheets,
- substituting a single sheet lining with external impervious tanks in chemicals storage areas should be considered at drill sites located in areas with a high background content of methane in soil gas and/or rich in organic matter,
- to design and develop the storm water draining system (a tight circular ditch, buried drainage system, tanks),
- additional ground protection in fuel, chemical and process fluid storage areas.

Besides the foregoing recommendations, it is vital to ensure ongoing supervision over drill site operations so as to enable immediate response in the event of an emergency.

In addition to measures intended to mitigate the risk of pollutant migration from the ground surface, it is important to consider potential migration of pollutants from the near well zone to deeper aquifers, including commercial ones. This may be due to inadequate well construction or completion, and first of all to deficient cementation (Labus, 2013). Considering that risk, it is recommended to:

- design well construction based on a thorough knowledge of the aquifer interval geology (placement of an additional casing string to the depth of aquifer occurrence),
- well tightness (cement bond integrity) testing immediately before and after fracture stimulation,
- identification of potential pollutant migration pathways in the aquifers (line of current determined using model studies),
- identification of existing groundwater intakes in the area of potential impacts,
- development of emergency action plan (in the event of a well failure).

As far as control of impact on the quantitative status of the waters is considered, it is recommended to deliver operations at each stage in accordance with the principle of rational water management. This means compliance with the principles of sustainable use of water resources considering actual user's needs (in terms of both quantity and quality) so as to not impair the status of the water. To ensure compliance of shale gas exploration and/or production with these principles, the following measures are recommended:

- a thorough investigation into actual water requirements of drill site operations (at all stages of work),
- to establish quality requirements for water used for different ends (which are different in case of water used for domestic purposes than those for water intended for hydraulic fluid preparation),
- to identify all the available sources of water supply to particular users, considering their actual requirements,
- to diversify water supply sources – available existing water supply sources (existing water intakes and supply networks, surface water, mine drainage waters, etc.) should be the first choice.

It should be emphasized that the use of an in-house water supply for construction purposes must comply with the procedures set forth by the provisions of Geological and Mining Law and Water Law on special use of waters under the water permit. Moreover, it must comply with the existing Conditions for the use of water in the water region and the Conditions for the use of water in the watershed (planning documents). Furthermore, land use prohibitions, injunctions or restrictions that apply to buffer zones of water intakes or freshwater reservoirs (including the Main Groundwater Reservoirs) must be considered in the decisions on the location of exploration/production projects. If the water is to be supplied from a well located at the drill site, it is recommended to include that well in the monitoring programme.

Concluding, shale gas exploration and/or production projects are recommended to comply with three basic rules that effectively mitigate the risk of water status impairment (Fig. 6.2). If combined with measures intended to prevent potential pollution, rational use of water resources and monitoring which is adequate to the local conditions, this will enable safe delivery of operations and an effective risk management.

Moreover, it should be emphasized that it is equally important to initiate new research projects aiming at the development of new safer and more environment-friendly technologies, for example reducing the water requirements of shale gas production. Similarly, new legislation that for example would enable the use of treated wastewater for hydraulic fracture stimulation, may contribute significantly to the control of potential impacts from extraction operation on the status of waters.

Fig. 6.2. Basic rules of water management in shale gas exploration and/or production.

6.3 Waste management

Based on the effected test site studies, wastes are produced at the drill site by the following operations:

- drilling operations,
- hydraulic fracture stimulation and gas-flow tests,
- day-to-day maintenance, upkeep and operation of drill site equipment.

The aforementioned operations produce the following waste categories:

- hazardous and non-hazardous drilling wastes – from drilling and hydraulic fracture stimulation operations;
- hazardous and non-hazardous wastes – from day-to-day maintenance, upkeep and operation of drill site equipment.

Waste management should comply with an approved Extractive Waste Management Programme, whilst other wastes should be managed according a waste production permit (if required). Request for any changes in extractive waste management programme (e.g. related to the volume of produced wastes or waste storage method) are submitted to the Local Assembly Speaker in jurisdiction over drill site location in the form of a declaration on the nature of changes and their approval should be in the form of a notice of acceptance.

Extractive wastes produced by exploration for unconventional hydrocarbons are managed by recycling/neutralisation processes. In case of these operations, the problem is that large volumes of wastes are produced over a short period of time. According to the existing regulations (Art. 7.2–3 of Extractive Waste Act of 10 July 2008, 2013 Journal of Laws, Item 1136, as amended), hazardous extractive wastes cannot be stored for a period longer than 6 months, while non-hazardous and inert wastes for more than 12 months before recycling or neutralisation.

Process wastes and fluids (fracturing and flowback fluids) generated by drilling and hydraulic fracture stimulation operations should be tested for characteristics and potential environmental risks in the event of uncontrolled release of the wastes or products of their recycling/neutralisation. The testing requirement is motivated by the use of chemical additives in fracturing fluid formulations and different geochemistry of the penetrated rocks. The tests are used to attribute the analysed waste/process fluid to hazardous or non-hazardous category and, by the same, to establish subsequent waste handling procedures (also considering the presence of radioactive isotopes).

In light of existing regulations and an analysis of the test site studies, it is recommended to:

- use test results at the development of extractive waste sheets, in accordance with Environment Minister's Ordinance of 20 June 2013 *on extractive waste data sheets* (2013 Journal of Laws, Item 759) and to indicate potential approach to waste handling, including the development of the criteria for recycling and/or neutralisation methods;

- to extent the scope of Waste Transfer Sheet by adding information about the final approach to waste handling and target delivery destination.

Development of extractive waste data sheets

Test results can be used to develop extractive waste data sheets, as required under Environment Minister's Ordinance of 20 June 2013 *on extractive waste data sheets* (2013 Journal of Laws, Item 759). Moreover, test result will facilitate the waste testing procedure and indicate potential parameters to be laboratory tested.

Ecotoxicity tests have demonstrated that spent mud, cuttings and flowback fluids may represent a threat (in case of inappropriate disposal) to living organisms if accidentally released to the environment; therefore, applicable regulations, as well as transport and reuse/neutralisation procedures should be strictly complied with.

The content of natural radioactive isotopes in spent mud, cuttings and flowback fluids were similar to average content in the soils (according to UNSCAR). A higher specific activity was reported from flowback proppant samples, but it was due to elevated (above soil average) content of ^{40}K. According to existing regulations, they do not represent a risk to the environment and human life. Therefore, in terms of natural radioactive isotope content the tested wastes are suitable for use in construction materials, site levelling and road building.

It should be noted that if wastes are used for land levelling, construction of roads and sports/recreational facilities, the absorbed dose rate from these facilities should be measured at a height of 1 m. According to Council of Ministers' Ordinance of 2 January 2007 *on the requirements concerning the contents of radioactive isotopes in buildings intended for occupation by people or livestock, on industrial wastes used in construction industry and on control of contents of these isotopes* (2007 Journal of Laws No. 4, Item 29), if wastes that comply with the f_1 and f_2 indices are used for land levelling, construction of roads and sports/recreational facilities, the dose rate absorbed 1 m above the ground, road or facility may not exceed 0.3 μGy/h (an additional layer of other material should be placed to ensure compliance with that requirement).

The results of tests and analyses are the basis for the development of waste reuse and/or inactivation criteria under applicable regulations. The development of such criteria would streamline the process of waste management and encourage research units and businesses to cooperate for the development of new extractive waste reuse/inactivation technologies.

Waste transfer sheets

Quantitative and qualitative records should be kept for each type of produced wastes in the form of Waste Record Sheet and Waste Transfer Sheet. Waste Record Sheet specifies the quantity of produced wastes by month and the approach to waste management. Waste Transfer Sheet specifies the waste holder who has accepted the waste, as well as the type and quantity of the delivered wastes.

Unfortunately, there is no obligation to provide information on the final destination and the approach to waste reuse/inactivation, although a cell to enter these data has been foreseen in the Waste Transfer Sheet. Operators and their subcontractors – the waste holders – should consider to disclose information about the final approach to waste management in Waste Transfer Sheets. This would provide the local communities, obviously interested in ensuring their own and environmental safety, with valuable information that, in addition, would help competent authority to supervise compliance with subsequent waste handling procedures.

6.4 Safety of production wells

Although shale gas is still to be produced in Poland, it would be of purpose to highlight safety aspects of shale gas production.

Active production wells probably will not require day-to-day maintenance, but experience from other countries, U.S.A. and Canada in particular, shows that wells may be productive for a period of several decades. Therefore, it is vital for both project viability and environmental protection to ensure well integrity over the entire period of operation. The annulus between casing strings and the

contact with penetrated rocks should be protected against accidental leaks of reservoir fluids (mainly gas) throughout drilling, fracturing and production operations.

Geophysical well logging data hep to assess geological formations and design the completion of the well. Moreover, several mechanical integrity tests and hydraulic pressure test are applied to check borehole integrity at well construction stage.

Cement bond testing is a key procedure for inspection of wells for integrity and technical status. The coat of cement that is part of the protective barrier at fracture stimulation and gas production, should be periodically inspected. Special more precise tools should be applied to check cement integrity in horizontal well legs. If technical condition of a well deteriorates (due to cement coat failure) as a result of fracture stimulation or prolonged production, remedial operations, that should be identified at the stage of risk assessment, are required. It is important to track any negative changes between the casing wall and cement throughout the period of production.

Technical plans and the frequency of integrity tests in production wells must depend on risk assessments made for each well and on technology of production. Well integrity checks should be delivered by the site operator according to the approved technical plan, in consultation with and under supervision of the regional mining office. Monitoring for potential gas emissions at the abandoned well location should be continued on production site closure and well abandonment.

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Appendices

Appendix 1 – Test site data sheets

Appendix 2 – Test site locations with regard to protected areas

Appendix 3 – List of potential environmental effects of unconventional oil and gas prospection and exploration operations

Appendix 1

TEST SITE DATA SHEETS

Appendix 1.1

TEST SITE DATA SHEET	LUBOCINO	page 1/3
TEST SITE	*name / designation*	**Lubocino / 1**
	well / Operator	**Lubocino-2H / PGNiG**
LOCATION		
	locality / commune / district / province	Lubocino / Krokowa / Puck / Pomeranian
	Concession area	Wejherowo
ENVIRONMENTAL CONDITIONS		
GEOGRAPHIC LOCATION		
	meso-region (acc. to Kondracki, 2006)	Żarnowiec High Plain
TERRAIN		
Several deep depressions (sub-glacial troughs and valleys) with high plains holms in-between		
The Żarnowiec Holm, altitudes ranging from 60 m in the north to over 100 m in the south, in the test site area; elevation gain from the surrounding plains (Krokowa Trough, Dobre Lake Trough, Żarnowiec Trough) is not in excess of 50 m; the drill site is located at the altitude of 102 m on a gentle slope of an elevation that has been levelled at drill site development stage		
HYDROGRAPHY		
WATERSHED		Watershed of Piaśnica River discharging directly to the Baltic Sea
THE NEAREST WATER COURSES / RESERVOIRS		
	name / distance from the well / direction	
		Czarna Woda / 3 km / NE
		Piaśnica / 3 km / S, W
		Dobre Lake / 1.5 km / SE
		Żarnowieckie Lake / 3.5 km / W
		a water hole / 0.8 km / S
		a water retention reservoir / 0.5 km / NW
HYDROGEOLOGICAL CONDITIONS		
MAIN COMMERCIAL AQUIFER (MCA)		
	stratigraphy	Q
	depth to aquifer	69 m b.g.l.
	type of water table	confined, stabilizes at a datum ranging from 15 to 40 m b.g.l.
	isolation from ground surface	partial (several metre thick boulder clay complex)
	filtration coefficient	0.00001–0.0001 m/s
	flow direction	SW towards the Żarnowieckie Lake Trough
	time of seepage from the ground surface	8-20 years
	total time of inflow of potential pollutants	50-60 years to the boundary of MGR 109
TOP AQUIFER (TA) – merges with main commercial aquifer in the test site area		
GROUNDWATERS (perched)		
	stratigraphy	Q
	depth to aquifer	layer I: 0.5-5 m b.g.l.; layer II: 26 m b.g.l.
	type of water table	unconfined
	isolation from ground surface	none (several metre thick sandy loams occur in places)
	filtration coefficient	0.00005–0.0001 m/s
	flow direction	N, NW, W
	time of seepage from the ground surface	8-11 years
	total time of inflow of potential pollutants	layer I approx. 10 years to the nearest hand-dug well; layer II approx. 20 years to the source
MAIN GROUNDWATER RESERVOIRS (MGR)		Żarnowiec Fossil Valley No. 19, located 1.5 km west of the drill site
GEOLOGY		
LOCATION		Peribaltic Syneclize, SE slope of the Łeba High
The Precambrian crystalline bedrock of metamorphic granitoids is overlain by terrestrial Eocambrian sediments (Żarnowiec Bed sandstones) that pass into marine Cambrian sediments (sandstones-mudstones interbedded with claystones - Lower Cambrian; sandstones with glauconite, claystones, mudstones - Middle Cambrian, prospective: showings of hydrocarbons reported, produced reservoirs in the area: Żarnowiec, Dębki, Białogóra; calcareous clayey sediments - Upper Cambrian); Cambrian sediments are overlain by discordant 50 to 90 m thick Ordovician claystones-mudstones deposited in shallow water; Ordovician formations are ovelain by a thick (1800 to 1900 m) cover of Silurian claystones and mudstones with calcareous intercalations; no Carboniferous, Devonian and Rotliegend sediments; Zechstein is represented by 3 cyclotems: Werra, Stassfurt and Leine; the diversely eroded Mesozoic formations include Bunter Sandstone, Triassic, Jurassic and Upper Cretaceous sediments; Cenozoic sands, gravels and mud/clayey sediments of diverse thicknesses cover the Mesozoic rocks		

TEST SITE DATA SHEET	LUBOCINO	page 2/3

CLIMATE

region	coastal region, highly variable weather, cool summers and mild winters
average annual temperature	+7.7°C
average annual precipitations	< 700 mm
predominant winds	S, SW
snow cover duration	40-60 days
vegetation period duration	up to 215 days

NATURE PROTECTION

area rank / name / straight line distance from the drill site / direction

nature reserve / Źródliska Czarnej Wody / 5.1 km / NE
protected landscape area / Puszcza Darżlubska / the drill site is located within the area
protected landscape area / Reda - Łeba Ice-marginal Valley / 9.5 km / S
Natura 2000 special protection area / Trzy Młyny / 3.3 km / NE
Natura 2000 special protection area / Opalińskie Buczyny / 6 km / SW
Natura 2000 special protection area / Puszcza Darżlubska / 8.9 km / SE
Natura 2000 special protection area / Orle / 10.8 km / S
ecological use / Święcińska Topiel (a community of rushes) / 1.7 km / NE
ecological use / Księża Łąka (a meadow and a fen) / 2.1 km / S
ecological use / Witalicz (a lake) / 2.7 km / NE

SPATIAL AND ECONOMIC CONDITIONS

NEIGHBOURHOOD

THE NEAREST COMMUNES

commune / straight line distance from the drill site

Puck / 10 km
Wejherowo / 2.6 km
Gniewino / 3.2 km
Choczewo / 12.0 km
Władysławowo / 15.5 km

THE NEAREST BUILDINGS

locality / type of buildings / straight line distance from the drill site / direction

Lubocino / isolated houses / 120 m / N
Lubocino / isolated houses / 180 m / W
Lubocino / isolated houses / 220 m / E
Lubocino / densely bulit-up area / 800 m / NW

LAND USE PATTERNS

the drill site located within arable fields is surrounded by farmland, small shrubs in proximity, a large forest complex is located 200-300 m S and E of the drill site

ACCESS

PROVINCIAL ROAD

provincial road number / section	218 / Krokowa – Gdańsk Osowa

ACCESS ROADS

road category / road surface / section	district / hardened / 2.6 km communal / soil-surfaced / 0.45 km

DEMOGRAPHY

POPULATION DENSITY

49 people / km^2

INFRASTRUCTURE

WATER SUPPLY PIPELINES	all households in the drill site area are connected to the water supply system with intakes at Karlików and Tyłów
SEWERAGE SYSTEMS	sewers in the nearest localities; overall, 67% of commune residents use sewerage systems; 4 wastewater treatment plants operated by a municipal utility company
HEAT SUPPLY	Individual heating systems, no centralized heat supply management
GAS SUPPLY NETWORK	Over 34% of the commune residents are gas network users

TEST SITE DATA SHEET	LUBOCINO	page 3/3
DRILL SITE OPERATOR		
PLOT OF LAND		
ref. number / size	71/12 / 2.0 ha	
DRILL SITE DEVELOPMENT		
PRELIMINARIES	levelling, topsoil recovered and stored in earthen embankments E of drill site; sand backfill, concrete slabs	
SEALING	wellhead area lined with sealing sheet	
DRAINAGE SYSTEM	three drainage tanks located at site angles	
PROCESS WATER TANKS	*type / quantity / capacity / footprint* earthen / 1 / 6000 m^3 / 0.45 ha	
DRILLING OPERATIONS		
MAIN CONTRACTOR	Poszukiwania Nafty i Gazu NAFTA S.A. in Piła (since 2013 Exalo)	
DURATION	August 2012 - October 2012	
FINAL LENGTH / DEPTH	3981 m (MD) / 2924 m (TVD)	
HORIZONTAL LEG: *length / direction*	936 m / S	
FRACTURING OPERATIONS		
MAIN CONTRACTOR	Halliburton Company	
DURATION	2 January 2013 – 11 February 2013	
FRACTURE STIMULATED SECTION	439 m in the interval of 3545 to 3106 m (MD)	
WATER AND PROPPANT VOLUMES USED	7696 m^3 of fracturing fluid / 244.65 tonnes of proppant	
FLOWBACK FLUID VOLUME	by 28 February 2013, 715 m^3 of flowback fluid recovered (approx. 9% of the total injected process fluids)	
GAS MANAGEMENT	Flare burning	
ADMINISTRATION		
CONCESSION		
NUMBER	4/2009/p	
GEOLOGICAL TARGET	to prove crude oil and natural gas resources	
VALID TILL	2021	
DECISION ON ENVIRONMENTAL PRECONDITIONS FOR PROJECT IMPLEMENTATION		
the undertaking was attributed to the projects that may have a significant effect on the environment (legislation status as of 2012) Decision by Regional Director for Environment Protection in Gdańsk of 14 March 2012		
OPERATIONS PLAN		
Decision by Director of District Mining Office in Poznań of 2 December 2010, ref. 070/0234/0086/10/08514/BA, on the approval of drill site operations plan		
WASTE MANAGEMENT		
drilling stage: no data provided (drilling contractor was in charge of waste management at the drilling stage) fracture stimulation stage: waste management programme approved by Pomeranian Local Assembly Speaker, decision of 5 October 2012, ref. DROŚ-S.7240,188,2012,NB; waste production permit approved by Puck District Head, decision of 16 July 2013, ref. ROŚ.6220.1.2012		
TESTS		
INITIAL STATUS		
as-found status: Lubocino-2H well included in the project is the second one drilled in that location, but the first one to have a horizontal leg; the first Lubocino – 1 well drilled in 2011 was three times fracture stimulated; on completion of tests under this project, the Operator started to drill Lubocino-3 well; the tests started in August 2012 before Lubocino-2H well was spud-in		
FINAL STATUS		
the second test round was delivered in June 2013, approx. 5 months after completion of fracture stimulation operations		

Appendix 1.2

TEST SITE DATA SHEET — STARE MIASTO — page 1/3

TEST SITE

name / designation **Stare Miasto / 2**

well / Operator **Stare Miasto-1K / ENI**

LOCATION

locality / commune / district / province Stare Miasto / Stary Dzierzgoń / Sztum / Pomeranian

Concession area Elbląg

ENVIRONMENTAL CONDITIONS

GEOGRAPHIC LOCATION

meso-region (acc. to Kondracki, 2006) Iława Lake District

TERRAIN

the youngest postglacial topography with highly variable recent landforms

within a rolling moraine high plain at altitudes above 30 m moraine hills with elevation gains up to 40 m occur; glaciofluvial valleys at the foot of morain hills; generally the terrain sloping towards the north to the Żuławy depression; near the drill site, altitudes reach 55 m and 40 m in the deeply inccised Dzierzgoń River valley; several metre high slopes of abandoned pits in the drill site proximity

HYDROGRAPHY

WATERSHED Dzierzgoń River (a Nogat River tributary) watershed

THE NEAREST WATER COURSES / RESERVOIRS

name / distance from the well / direction

Dzierzgoń / 1.1 km / N

an abandoned pit reservoir ("Dzierzgoń - Stare Miasto II deposit) / <0.1 km / N

HYDROGEOLOGICAL CONDITIONS

MAIN COMMERCIAL AQUIFER (MCA)

stratigraphy Q

depth to aquifer 20 m b.g.l.

type of water table confined, stabilizes at 2.15-2.60 m b.g.l.

isolation from ground surface approx. 20 m, in the drill site area approx. 10 m

filtration coefficient 0.000046 m/s

flow direction N-NW, towards Dzierzgoń River

time of seepage from the ground surface 70 days*(to the TA near the drill site)*

total time of inflow of potential pollutants 2.5 years – to the local drainage base (the Dzierzgoń River)

TOP AQUIFER (TA)

stratigraphy Q

depth to aquifer 5-10 m b.g.l.

type of water table confined, stabilizes at 3.5-7.9 m b.g.l.; locally unconfined

isolation from ground surface 5-10 m

filtration coefficient 0.000023 m/s

flow direction N-NW, towards Dzierzgoń River

time of seepage from the ground surface 70 days*(to the TA near the drill site)*

total time of inflow of potential pollutants 70 days (*vertical component*) + 2.5 years *(horizontal component)*

drainage base: Dzierzgoń River

MAIN GROUNDWATER RESERVOIRS (MGR) Iława Reservoir No. 210, located 4.5 km SWW of the drill site

GEOLOGY

LOCATION Peribaltic Syneclize

the oldest Precambrian formations (leptite gneiss) occur at a depth of approx. 3890 m; they are overlain by a 1630-1870 m thick complex of Paleozoic sedimentary rocks (mudstones, sandstones, including glauconite ones, claystones and mudstones; Middle Cambrian formations are overlain by Lower Ordovician glauconite sandstones and Middle/Upper Ordovician black clay shales with graptolites; black mudstone and siliceous clay shales with graptolite fauna, about 725 m thick in the profile of Stare Miasto-1 well, were deposited as a result of early Silurian marine transgression; Devonian and Carboniferous formations are missing; the Permian sequence (Zechstein, including Werra, Stassfurt and Leine cyclotems) was deposited on partly eroded Silurian sediments; Mesozoic formations start with Lower Triassic terrestrial or laguna claystone/mudstone sediments in the Bunter sandstone facies, followed by Middle Triassic carbonate rocks and Upper Triassic sandstones and claystones/mudstones; total Triassic thickness is about 600 m; Triassic is overlain by approx. 450-550 m Jurassic formations: terrestrial sediments (clays, claystones, mudstones, sandstones - Lower Jurassic; conglomerates, sands, sandstones - lower Middle Jurassic) and marine sediments (Middle Jurassic claystone/mudstone and clayey/sandstone facies and Upper Jurassic calcareous sandstones, marls, mudstones and clays); the Cretaceous claystones/mudstones, quartz-glauconite sandstones, calcareous and marly mudstones, gaizes and amrls are approx. 400-600 m thick; Paleogene is represented by fine-grained Paleocene sands and Oligocene sands and loose sands; Quaternary sediments, in the form of glacial and interglacial deposits and Holocene sediments, are on average 120 m thick

TEST SITE DATA SHEET	STARE MIASTO	page 2/3

CLIMATE

region	Pomerania-Warmia region, climate is generally cooler than in central Poland
average annual temperature	+7.3°C
average annual precipitations	600-700 mm
predominant winds	NW, W
snow cover duration	80 days
vegetation period duration	180-190 days

NATURE PROTECTION

area rank / name / straight line distance from the drill site / direction

nature reserve / Druzno Lake / 18 km / NE
Iława Lake District Scenic Park / 7 km / SE
Dzieżgoń River Protected Landscape Area / 5 km / W
Dzieżgoń Lake Protected Landscape Area / <0.1 km / N
Druzno Lake Protected Landscape Area / 18 km / NE
Natura 2000 special habitat protection area / Ostoja Iławska / 7 km / NE
Natura 2000 special habitat protection area / Aleje Pojezierza Iławskiego / 10 km / S
Natura 2000 special habitat protection area / Mikołajki Pomorskie / 13 km / SW
Natura 2000 special habitat protection area / Druzno Lake / 18 km / NE
Natura 2000 special habitat protection area / Budwity / 19 km / E
Natura 2000 special bird protection area / Iława Forests / 7 km / SE
Natura 2000 special bird protection area / Druzno Lake /18 km / NE
ecological use / Tywęzy (water reservoirs) / 6 km / W
natural-landscape complex / Jare (oak trees) / 5 km / N

SPATIAL AND ECONOMIC CONDITIONS

NEIGHBOURHOOD

THE NEAREST COMMUNES

commune / straight line distance from the drill site

Dzierzgoń / 2 km
Rychliki / 5.5 km
Małdyty / 13 km
Zalewo / 10 km
Susz / 8 km
Prabuty / 8.5 km
Mikołajki Pomorskie / 4.5 km

THE NEAREST BUILDINGS

locality / type of buildings / straight line distance from the drill site / direction

Stare Miasto / compact farmsteads / 650 m / NW

LAND USE PATTERNS: the drill site is located near active aggregate pits and farmland, an extensive forest complex Zakręcki Las is located at a distance of 600 m S and SW from the drill site

ACCESS

PROVINCIAL ROAD

provincial road number / section: 515 / Malbork-Susz

ACCESS ROADS

road category / road surface / section: local / paved with concrete slabs / 0.1 km

DEMOGRAPHY

POPULATION DENSITY

22 people / km^2

INFRASTRUCTURE

WATER SUPPLY PIPELINES	all households in the drill site area are connected to water supply systems with an intake in Stare Miasto; overall, 77% of the commune residents are water supply system users; residents of villages that are not connected to water supply systems use drilled and hand-dug water wells
SEWERAGE SYSTEMS	The nearest localities are not equipped with sewerage systems; overall, 12% of all commune residents use sewerage systems, Przezmark and Myślice are the only localities with sewerage systems; 2 waste-water treatment plants are operated by a local municipal utility
HEAT SUPPLY	Individual heating systems, no centralized heat supply management
GAS SUPPLY NETWORK	none

TEST SITE DATA SHEET	STARE MIASTO	page 3/3

DRILL SITE OPERATOR

PLOT OF LAND

ref. number / size	349/2 / 2.3 ha

DRILL SITE DEVELOPMENT

PRELIMINARIES	levelling, topsoil recovered and stored in earthen embankments S of drill site; sand backfill, concrete slab s
SEALING	PEHD sheet lining over the entire drill site area
DRAINAGE SYSTEM	internal circular drainage of the so-called dirty area, with oil and solids separator, external circular drainage, two drainage tanks located N of the drill site
PROCESS WATER TANKS	*type / quantity / capacity / footprint* pillow tanks / 8 / 190 m^3 each / 0.4 ha

DRILLING OPERATIONS

MAIN CONTRACTOR	DrillTec GUT GmbH Grossbohr - und Umwelttechnik
DURATION	April 2012 - July 2012
FINAL LENGTH / DEPTH	3490 m (MD) / 2955 m (TVD)
HORIZONTAL LEG: *length / direction*	300 m / E-NE

FRACTURING OPERATIONS

MAIN CONTRACTOR	Schlumberger
DURATION	2 October 2012 - 6 October 2012
FRACTURE STIMULATED SECTION	247 m in the interval of 3446 m to 3282 m (MD)
WATER AND PROPPANT VOLUMES USED	3431 m^3 of fracturing fluid / 203.2 tonnes of proppant
FLOWBACK FLUID VOLUME	758 m^3 of flowback fluid (approx. 22% of the total injected process fluids) recovered
GAS MANAGEMENT	Flare burning

ADMINISTRATION

CONCESSION

NUMBER	29/2008/p
GEOLOGICAL TARGET	to prove natural gas accumulations in Silurian, Ordovician and Cambrian formations
VALID TILL	2015

DECISION ON ENVIRONMENTAL PRECONDITIONS FOR PROJECT IMPLEMENTATION

the undertaking was attributed to the projects that potentially may have a significant effect on the environment (legislation status as of 2012)
Decision by Regional Director for Environment Protection in Gdańsk of 14 March 2012

OPERATIONS PLAN

Decision by Director of District Mining Office in Poznań of 21 September 2012, ref. 087/0234/0020/12/06282/KM, on the approval of supplement 7 to the drill site operations plan

WASTE MANAGEMENT

waste management programme approved by Pomeranian Local Assembly Speaker, decision of 6 August 2012, ref. DROŚ-S.7240.148.2012.NB;
hazardous waste management programme approved by Sztum District Head, decision of 13 August 2012, ref.: OS.6230.2.2012.MK

TESTS

INITIAL STATUS

as-found status: the Stare Miasto-1K well runs from the previously drilled Stare Miasto-1 vertical well;
the tests started in August 2012 at horizontal leg drilling stage

FINAL STATUS

the second test round was delivered in October 2012, about six months of fracture stimulation completion; an additional test round was delivered in 2014 following site reclamation operations

Appendix 1.3

TEST SITE DATA SHEET	SYCZYN	page 1/3

TEST SITE

name / designation **Syczyn / 3**

well / Operator **Syczyn OU-2K / ORLEN UPSTREAM**

LOCATION

locality / commune / district / province Syczyn / Wierzbica / Chełm / Lublin

Concession area Wierzbica

ENVIRONMENTAL CONDITIONS

GEOGRAPHIC LOCATION

meso-region (acc. to Kondracki, 2006) Łęczna-Włodawa Plain

TERRAIN

an extensive flat marshy plain with several fens, peat bogs, small lakes, numerous thermokarst and karst hollows; elevations are little diversified in the test site are and are mostly in the order of 180 m, the terrain is lightly sloping southward towards the Syczyńskie Lake

HYDROGRAPHY

WATERSHED Świnka River (a Wieprz River tributary) watershed

THE NEAREST WATER COURSES / RESERVOIRS

name / distance from the well / direction

Świnka / 3 km / W-SW

Lepitucha / 3 km / E-SE

Syczyńskie Lake / 0.6 km / S

numerous streams, channels and a complex drainage ditch system

HYDROGEOLOGICAL CONDITIONS

MAIN COMMERCIAL AQUIFER (MCA)

stratigraphy	Q-Cr
depth to aquifer	5-15 m b.g.l.
type of water table	mostly unconfined
isolation from ground surface	poor or absent
filtration coefficient	0.00016 m/s – Cr; 0.000035 m/s – Q
flow direction	NWW
time of seepage from the ground surface	107 days
total time of inflow of potential pollutants	• to the Ludwinów water intake: approx. 20 years (7300 days) • to the Świnka River: approx. 10 years (3650 days) • to the MGR 407: 3 months

THE TOP AQUIFER (TA) is THE MAIN COMMERCIAL AQUIFER (MCA)

stratigraphy	
depth to aquifer	
type of water table	
isolation from ground surface	
filtration coefficient	
flow direction	
time of seepage from the ground surface	
total time of inflow of potential pollutants	

MAIN GROUNDWATER RESERVOIRS (MGR) Chełm-Zamość No. 407, the drill site is located with the Reservoir area

GEOLOGY

LOCATION Lublin Basin

The oldest Precambrian rocks are Proterozoic granitoids or migmatites, overlain by Neoproterozoic sandstones and mudstones, followed by approx. 600 m thick Cambrian sandstones and mudstones; the thickness of Ordovician limestones, marls, siliceous and clastic sediments is in the order of several tens of metres; the Silurian rocks, mainly in the form of calcareous claystones and mudstones with limestone lentils and locally carbonaceous organic matter, are over 800 m thick; Devonian sediments, over 500 m thick, include quartz sandstones, mudstones, claystones, organo-dendritic limestones; the Carboniferous is represented by all the members known from the Lublin Coal Basin, the main coal deposits are associated with the Lublin Beds in the Carboniferous top; the Jurassic limestones and marls are 50-100 m thick; Cretaceous is in the form of little diagenetically transformed carbonate (chalk), carbonate-clayey (marls, marly limestones) and carbonate-siliceous (gaizes, marly gaizes) rocks; in total, Cretaceous sediements are over 500 m thick; Cretaceous top occurs at various depths due to erosional processes at the surface of carbonate rocks; Quaternary sediments associated with depositional activity of the Central Polish Glaciation are 28 m thick in the drill site area and are composed of sandy silts with loams and sands at the top; locally, peat deposits of a small thickness occur

TEST SITE DATA SHEET	SYCZYN	page 2/3

CLIMATE

region	the Chełm Region, moderate climate with continental features
average annual temperature	+7.2 °C
average annual precipitations	500-600 mm
predominant winds	W, SW
snow cover duration	85-90 days
vegetation period duration	214-216 days

NATURE PROTECTION

area rank / name / straight line distance from the drill site / direction

national park / Polesie National Park / 6 km / NE
reserve / Świerszczów Lake (aquatic and plant reserve) / 6.5 km / NW
scenic park / Chełm Scenic Park / 10 km / E
scenic park / Polesie Scenic Park / 13 km / N
scenic park / Łęczna Scenic Park / 5.5 km / N
scenic park / Wieprz Scenic Park / 7 km / W-SW
protected landscape area / Chełm area / the drill site is located within the area
Natura 2000 special habitat protection area / Ostoja Poleska / 6 km / N
Natura 2000 special habitat protection area / Sierniawy/ 9 km / NE
Natura 2000 special habitat protection area / Bachus / 13 km / NE
Natura 2000 special habitat protection area / Sawin / 10 km / E
Natura 2000 special habitat protection area / Stawska Góra / 14 km / SE
Natura 2000 special habitat protection area / Nowosiółki (Julianów) / 12 km / SE
Natura 2000 special habitat protection area / Pawłów / 12 km / S
Natura 2000 special habitat protection area / Dobromyśl / 7 km / SW
Natura 2000 special habitat protection area / Uściwierz Lakes / 11 km / NW
Natura 2000 special bird protection area / Polesie / 11 km / NW

SPATIAL AND ECONOMIC CONDITIONS

NEIGHBOURHOOD

THE NEAREST COMMUNES

commune / straight line distance from the drill site

Cyców / < 1 km	Sawin / 10 km
Urszulin / 5.5 km	Siedliszcze / 2.5 km
Hańsk / 10 km	Chełm / 10.5 km

THE NEAREST BUILDINGS

locality / type of buildings / straight line distance from the drill site / direction

Syczyn / isolated buildings / 50 m / W
Syczyn / compact farmsteads / 200 m / S

LAND USE the drill site is located among farmland and meadows, the Las Syczyński forest complex is situated at a distance of 500 m northward of the drill site; the drill site is within the boundaries of the Lublin K-8 coal deposit which is not produced as conflicting with water protection requirements

ACCESS

PROVINCIAL ROAD

provincial road number / section 841 / Cyców-Horodyszcze

ACCESS ROADS

road category / road surface / section

from Cyców: district road / hardened / 5 km
district / hardened / 0.6 km
access / paved with concrete slabs / 0.15 km
from Werejce: local / hardened / 3 km
district / hardened / 0.3 km
access / paved with concrete slabs / 0.15 km

DEMOGRAPHY

POPULATION DENSITY

37 people / km^2

INFRASTRUCTURE

WATER SUPPLY PIPELINES	all households in drill site neighbourhood have access to the local water supply system with intake at Wierzbica; more than 64% of commune residents use water supply systems
SEWERAGE SYSTEMS	26% of commune residents are sewerage system users
HEAT SUPPLY	Individual heating systems, no centralized heat supply management
GAS SUPPLY NETWORK	none

TEST SITE DATA SHEET	SYCZYN	page 3/3
DRILL SITE OPERATOR		
PLOT OF LAND		
ref. number / size	195, 196, 197 / 2.6 ha	
DRILL SITE DEVELOPMENT		
PRELIMINARIES	levelling, topsoil recovered and stored in earthen embankments W of drill site; sand backfill, concrete slabs	
SEALING	PEHD sheet lining over the entire drill site area	
DRAINAGE SYSTEM	circular drainage ditch, drainage tank located in NE part of the drill site	
PROCESS WATER TANKS	*type / quantity / capacity / footprint* earthen / 2 / 21060 m^3 + 12848 m^3 / 0.9 ha	
DRILLING OPERATIONS		
MAIN CONTRACTOR	Poszukiwania Nafty i Gazu NAFTA S.A. in Piła (since February 2013 Exalo)	
DURATION	September 2012 - November 2012	
FINAL LENGTH / DEPTH	4100 m (MD) / 2635.9 m (TVD)	
HORIZONTAL LEG: *length / direction*	approx. 1500 m / E	
FRACTURING OPERATIONS		
MAIN CONTRACTOR	Schlumberger	
DURATION	20 May 2013 - 4 June 2013	
FRACTURE STIMULATED SECTION	horizontal	
WATER AND PROPPANT VOLUMES USED	38145.7 m^3 of fracturing fluid / 1392.8 tonnes of proppant	
FLOWBACK FLUID VOLUME	7866.2 m^3 of proppant fluid (approx. 20.6% of the total injected process fluids) recovered	
GAS MANAGEMENT	Flare burning	
ADMINISTRATION		
CONCESSION		
NUMBER	28/2007/p	
GEOLOGICAL TARGET	to prove crude oil and natural gas resources	
VALID TILL	2016	
DECISION ON ENVIRONMENTAL PRECONDITIONS FOR PROJECT IMPLEMENTATION		
the undertaking was attributed to the projects that potentially may have a significant effect on the environment (legislation status as of 2012) Wierzbica Mayor's decision of 17 October 2012		
OPERATIONS PLAN		
Decision by Director of District Mining Office in Lublin of 14 September 2012, ref. LUB/0234/96/12/JN, on the approval of drill site operations plan Decision by Director of District Mining Office in Lublin of 20 November 2012, ref. LUB/0234/118/12/JN, on the approval of supplement 1 to drill site operations plan		
WASTE MANAGEMENT		
waste management programme approved by Lublin Local Assembly Speaker, decision of 23 July 2012, ref. RŚ.V.7240.72.2012.EW;		
TESTS		
INITIAL STATUS		
as-found status; horizontal Syczyn OU-1 well; tests started in October 2012, at Syczyn OU-2K well drilling stage, additional tests made in April 2013		
FINAL STATUS		
a test round was made in October 1013, three months after fracture stimulation; a test round was made in July 2014, twelve months after fracture stimulation		

Appendix 1.4

TEST SITE DATA SHEET	WYSIN	page 1/3

TEST SITE

name / designation	**WYSIN / 4**
well / Operator	**Wysin-1 / PGNiG**

LOCATION

locality / commune / district / province	Stary Wiec / Liniewo / Kościerzyna / Pomeranian
Concession area	Stara Kiszewa

ENVIRONMENTAL CONDITIONS

GEOGRAPHIC LOCATION

meso-region (acc. to Kondracki, 2006)	Kaszuby Lake District

TERRAIN

young-glacial moraine high plain with numerous frontal moraine hills

altitudes ranging from 200 to220 m in northern part of the area, culminating at 246.3 m, decrease southward to approx. 140-130 m; in the drill site area, altitudes are in the order of 165 m. ; hill elevation is mostly in the order of 10 to 25 m; up to 30 m deep postglacial troughs, mostly filled with lakes, add to the scenery

HYDROGRAPHY

WATERSHED: Wietcisy River (Wierzyca River tributary) watershed

THE NEAREST WATER COURSES / RESERVOIRS

name / distance from the well / direction

Wietcisa / 0.8 km / S

Starowieckie Lake / 1.8 km / N

HYDROGEOLOGICAL CONDITIONS

MAIN COMMERCIAL AQUIFER (MCA)

stratigraphy	Q
depth to aquifer	20-50 m b.g.l., shallower in the Wietcisa River Valley
type of water table	confined
isolation from ground surface	15-50 m
filtration coefficient	0.000117 m/s-0.000776 m/s
flow direction	S, towards the Wietcisa River
time of seepage from the ground surface	4.3 years
total time of inflow of potential pollutants	a distance of 900-1000 m, 6-7 years

THE TOP AQUIFER (TA) merges with the main commercial aquifer to form a single system with similar flow direction and shared drainage base

stratigraphy	
depth to aquifer	
type of water table	
isolation from ground surface	
filtration coefficient	
flow direction	
time of seepage from the ground surface	
total time of inflow of potential pollutants	

MAIN GROUNDWATER RESERVOIRS (MGR): Gołebiewo Intra-moraine Reservoir No. 115; the drill site is located within the reservoir contour

GEOLOGY

LOCATION: Peribaltic Syneclize, eastern margin of the Łeba High

Older Paleozoic and Permian-Mesozoic structural complexes are deposited on the denuded crystalline bedrock; the older Paleozoic sedimentation starts with a series of continental sediments, the so-called *Żarnowiec Beds* deposited in huge alluvial cones and by meandering rivers; the continental sediments and Lower/Middle Cambrian formations (Upper Cambrian formations have been largely stripped by erosion) form a single sedimentary complex, overlain by Ordovician and Silurian formations with erosional and sedimentary gaps; Mesozoic sedimentation starts with Buntsandstein claystone-mudstones with intercalations of carbonate rocks; the overlying Muschelkalk which comprises marls, dolomites with limestone intercalations and claystones, passing into sandstone at the top is followed by Lower, Middle and Upper Jurassic formations, locally with stratigraphic and erosional gaps covering various Jurassic members; Cretaceous sediments lie discordantly on the Jurassic: Lower Cretaceous sands and mustones and Upper Cretaceous glauconite sandstones, marly limestones and marls; incomplete Tertiary sediments are represented by Miocene carbonaceous silty clays interbedded with sandy silts; Quaternary sediments include a series of glacial and glaciofluvial sediments of the South, Central and North Polish Glaciations; the sediments of North Polish Glaciation stages are found in troughs and valley deeply cut into the Tertiary basement; sands, sand and gravel sediments frequently with pebbels found beneath, in between and above the boulder clays, are of glacial and periglacial origin.

TEST SITE DATA SHEET	WYSIN	page 2/3

CLIMATE

region	Pomeranian region, high weather variability and diversity
average annual temperature	+7.2°C
average annual precipitations	550 mm
predominant winds	W, NW
snow cover duration	50-70 days
vegetation period duration	210-220 days

NATURE PROTECTION

area rank / name / straight line distance from the drill site / direction

scenic park / Kaszuby Scenic Park / 13 km / NE
protected landscape area / Wietcisa / 1 km / E, S, W
Natura 2000 special habitat protection area / Lubieszynek / 5 km / W
Natura 2000 special habitat protection area / Middle Wietcisa Valley / 4 km / NW
Natura 2000 special habitat protection area / Szumleś / 7 km / NW
Natura 2000 special habitat protection area / Guzy / 6 km / N
Natura 2000 special habitat protection area / Zielenin / 4 km / NE
Natura 2000 special habitat protection area / Szczodrowo / 5 km / E
Natura 2000 special habitat protection area / Wierzyca Valley / 6 km / S
Natura 2000 special bird protection area / Bory Tucholskie / >15 km / W, SW

SPATIAL AND ECONOMIC CONDITIONS

NEIGHBOURHOOD

THE NEAREST COMMUNES

commune / straight line distance from the drill site

Stara Kiszewa / 7.5 km
Kościerzyna / 12 km
Nowa Karczma / 3.6 km
Skarszewy / 1.9 km

THE NEAREST BUILDINGS

locality / type of buildings / straight line distance from the drill site / direction

Stary Wiec/ farmsteads / 1 km / E
Wysin / farmsteads / 1 km / W

LAND USE PATTERNS

the drill site is surrounded by arable fields, cropland in immediate drill site proximity

ACCESS

PROVINCIAL ROAD

provincial road number / section 224 / Tczew-Wejherowo

ACCESS ROADS

road category / road surface / section from Głodowo: district road / asphalted / 4 km
from Lubieszyno: district road / asphalted / 5 km

DEMOGRAPHY

POPULATION DENSITY

42 people / km^2

INFRASTRUCTURE

WATER SUPPLY PIPELINES	households in drill site area and the drill site are provided with water from a local water supply system almost 88% of the commune residents are water supply system users
SEWERAGE SYSTEMS	46% of commune residents are sewerage system users
HEAT SUPPLY	Individual heating systems, no centralized heat supply management
GAS SUPPLY NETWORK	the local gas distribution network is only 1.2 km long, 0.2% of commune residents are gas supply system users

TEST SITE DATA SHEET	WYSIN	page 3/3

DRILL SITE OPERATOR

PLOT OF LAND

ref. number / size	175/7 / 1.5 ha

DRILL SITE DEVELOPMENT

PRELIMINARIES	levelling, topsoil recovered and stored in earthen embankments E and W of drill site; geomembrane; sand backfill, concrete slabs
SEALING	sheet lining over the entire drill site area
DRAINAGE SYSTEM	circular drainage ditch, two drainage tanks located in S part of the drill site
PROCESS WATER TANKS	*type / quantity / capacity / footprint* none

DRILLING OPERATIONS

MAIN CONTRACTOR	Exalo Drilling PGNiG Group
DURATION	March 2013 - May 2013
FINAL LENGTH	4040 m (MD)
HORIZONTAL LEG: *length / direction*	NONE

FRACTURE STIMULATION not applicable

MAIN CONTRACTOR	
DURATION	
FRACTURE STIMULATED SECTION	
WATER AND PROPPANT VOLUMES USED	
FLOWBACK FLUID VOLUME	
GAS MANAGEMENT	

ADMINISTRATION

CONCESSION

NUMBER	1/2011/p
GEOLOGICAL TARGET	to prove crude oil and natural gas resources
VALID TILL	2017

DECISION ON ENVIRONMENTAL PRECONDITIONS FOR PROJECT IMPLEMENTATION

the undertaking was attributed to the projects that potentially may have a significant effect on the environment (legislation status as of 2010)
the decision of Regional Director for Environmental Protection in Gdańsk of 10 September 2010 on environmental preconditions, ref. RDOŚ-22-WOO.6670/26-12/08/09/10ER

OPERATIONS PLAN

the decision by Director of District Mining Office in Poznań of 6 March 2013, ref. POZ0234.83.2013.EC/KM on the approval of drill site operations plan

WASTE MANAGEMENT

waste management programme approved by Pomeranian Local Assembly Speaker, decision of 21 December 2012, ref. DROŚ-S.7240.231.2012.EB;
hazardous waste management programme approved by Kościerzyna District Head, decision of 14 January 2012, ref.: OŚ.6230.4.2012

TESTS

INITIAL STATUS

baseline status
the tests started in September 2012 before the beginning of drill site development

FINAL STATUS

tests made during drilling operations, from March to May 2013
as the well was not fracture stimulated, the tests planned for this project were discontinued;
on drill site abandonment soil air tests were made under the sealing sheet in order to check for accumulation of gas from different sources under the impervious lining

Appendix 1.5

TEST SITE DATA SHEET — ZAWADA — page 1/3

TEST SITE

name / designation **Zawada / 5**

well / Operator **Zwierzyniec-1 / Chevron Polska**

LOCATION

locality / commune / district / province Zawada / Zamość / Zamość / Lublin

Concession area Zwierzyniec

ENVIRONMENTAL CONDITIONS

GEOGRAPHIC LOCATION

meso-region (acc. to Kondracki, 2006) Zamość Basin

TERRAIN

an extensive basin with prominent edges of surrounding hills

altitudes range from 210 to 260 m, the terrain is mostly flat with extensive humps and inselbergs raising to 10-20 m above the basin's bottom and dividing extensive dry gently sloped valleys

HYDROGRAPHY

WATERSHED Łabuńka River (a Wieprz River tributary) watershed

THE NEAREST WATER COURSES / RESERVOIRS

name / distance from the well / direction

Łabuńka / 6 km / N

Wieprz / 7 km / SW

HYDROGEOLOGICAL CONDITIONS

MAIN COMMERCIAL AQUIFER (MCA)

stratigraphy Cr

depth to aquifer 20 m b.g.l.

type of water table mostly unconfined

isolation from ground surface none or poor

filtration coefficient 0.0000188 m/s

flow direction N-NNE, towards the Łabuńka River

time of seepage from the ground surface 725 days

total time of inflow of potential pollutants 15-20 years – to the local drainage base (Łabuńka River)

THE TOP AQUIFER (TA) is THE MAIN COMMERCIAL AQUIFER

stratigraphy

depth to aquifer

type of water table

isolation from ground surface

filtration coefficient

flow direction

time of seepage from the ground surface

total time of inflow of potential pollutants

MAIN GROUNDWATER RESERVOIRS (MGR) Chełm-Zamość No. 407, the drill site is located with the Reservoir area

GEOLOGY

LOCATION NW part of Lublin Basin

the test site is located at the Radom-Kraśnik Elevation with uplifted lower Paleozoic formations and a reduced thickness of the Mesozoic caprock, numerous stratigraphic gaps, highly variable stratigraphy, thicknesses, uplifiting and stripping degree and with sedimentary gaps; Lower Silurian formations are the main exploration target at Zwierzyniec Concession: the Wenlockian dark grey and black slightly calcareous graptolite shales; lower Llandovery dark grey and black, frequently calcareous, graptolite shales interbedded with dolomitic mudstones; Upper Silurian reservoir rocks are the secondary exploration target: Lludlowian grey and dark grey laminated fissile calcareous claystones and mudstones with graptolites; Pridolian sediments are mostly composed of greywackes with beds of grey calcareous claystones and infrequent layers with graptolites; Devonian and Carboniferous rocks were not found in the profile of Zwierzyniec-1 well; Devonian or Devonian and Carboniferous formations were reported from neighbouring wells, but Permian and Triassic were not found in any of them; the Paleozoic basement is overlain by a sequence of Mesozoic formations starting with carbonate Middle and Upper Jurassic rocks, in total approx. 460 m thick; Upper Jurassic rocks are discordantly overlain by an approx. 920 m thick complex of Cretaceous marine carbonate sediments, mostly light grey marly limestones passing into marls with gaize layers at the top; no extant Paleogene and Neogene sediments; Quaternary sediments, predominantly of fluvial, but also of aeolian and deluvial origin, have been deposited on a morphologically diversified Cretaceous top; in the drill site area, loesses of fluvial-periglacial origin form an extensive cover of older Quaternary rocks; Holocene sediments are represented by silts and sands of the flood terraces, peats, peaty silts, muds of landlocked depressions and river valleys, as well as by deluvial sands and silts.

TEST SITE DATA SHEET	ZAWADA	page 2/3

CLIMATE

region	Lublin Zamość Region, relatively short transitional seasons
average annual temperature	+7.5°C
average annual precipitations	600 mm
predominant winds	S, SW, NW
snow cover duration	80-100 days
vegetation period duration	210-220 days

NATURE PROTECTION

area rank / name / straight line distance from the drill site / direction

national park / Roztocze National Park / 9 km / S
reserve / Hubale (fauna protection reserve) / 7.5 km / SE
reserve / Wieprzec (peat bog protection reserve) / 8 km/ SE
scenic park / Skierbieszowski / 7 km / NE
scenic park / Łęczna Lake District / 5.5 km / N
scenic park / Wieprz Scenic Park / 7 km / W-SW
Natura 2000 special habitat protection area / Roztocze Środkowe / 9 km / S
Natura 2000 special habitat protection area / Hubale / 7.5 km / SE
Natura 2000 special habitat protection area / Łabuńka and Topornica Valleys / 8 km / NE
Natura 2000 special habitat protection area / Niedzieliski Las / 3 km / E
Natura 2000 special habitat protection area / Niedzieliska / 4.5 km / SE
Natura 2000 special habitat protection area / Kąty / 6 km / SE
Natura 2000 special habitat protection area / Łętownia Valley / 10.5 km / NW
Natura 2000 special habitat protection area / Kornelówka / 15 km / NW
Natura 2000 special bird protection area / Roztocze / 3.5 km / S
Natura 2000 special bird protection area / Upper Łabuńka Valley / 8 km / S
Natura 2000 special bird protection area / Ostoja Nieliska / 5 km / NW

SPATIAL AND ECONOMIC CONDITIONS

NEIGHBOURHOOD

THE NEAREST COMMUNES

commune / straight line distance from the drill site

Szczebrzeszyn / 1 km
Sułów / 3.2 km
Nielisz / 1.5 km
Stary Zamość / 6.0 km
Zamość city / 5.5 km

THE NEAREST BUILDINGS

locality / type of buildings / straight line distance from the drill site / direction

Kolonia Siedliska / isolated buildings / 1 km / E, SE
Zawada / compact farmsteads / 1.5 km / S

LAND USE: the drill site is located among arable fields in immediate neighbourhood of cropland; according to the local planning and zoning scheme for the Commune of Zamość, the area is characterized by the presence of farms and good soils and is designated primarily for production of food;
A proven deposit of ceramic clay is located 550 m SE of the drill site; the deposit is not exploited due to a conflict (protected soils) and land management patters (railway and power transmission facilities)

ACCESS

PROVINCIAL ROAD

provincial road number / section national road 74 / Sulejów-Zosin

ACCESS ROADS

road category / road surface / section local / field road / 1.5 km

DEMOGRAPHY

POPULATION DENSITY

113 people / km^2

INFRASTRUCTURE

WATER SUPPLY PIPELINES	In the drill site area, households are supplied with water from individual wells to the Cretaceous aquifer, in localities situated east of the drill site the water is supplied from an intake at Szczebrzeszyn
SEWERAGE SYSTEMS	10% of commune residents are sewerage system users; a highly dispersed settlement is the key problem faced by sewer system development
HEAT SUPPLY	Individual heating systems, no centralized heat supply management
GAS SUPPLY NETWORK	40% of commune residents are gas supply system users

TEST SITE DATA SHEET	ZAWADA	page 3/3

DRILL SITE OPERATOR

PLOT OF LAND

ref. number / size	894, 895 / 2.7 ha

DRILL SITE DEVELOPMENT

PRELIMINARIES	levelling, topsoil recovered and stored in earthen embankment around the drill site; sand backfill, concrete slabs
SEALING	sheet lining over the entire drill site area
DRAINAGE SYSTEM	circular drainage ditch, drainage tank located in E part of the drill site
PROCESS WATER TANKS	*type / quantity / capacity / footprint* containers / - / 1512 m^3 / -

DRILLING OPERATIONS

MAIN CONTRACTOR	Hydro-Nafta Sp z o.o. (to 54 m b.g.l.) Poszukiwania Nafty i Gazu NAFTA S.A. in Piła (since 2013 Exalo Drilling PGNiG Group
DURATION	December 2012 - February 2013
FINAL DEPTH	3192 m (TVD)
HORIZONTAL LEG: *length / direction*	NONE

FRACTURING OPERATIONS

MAIN CONTRACTOR	Halliburton
DURATION	6 July 2013 - 10 July 2013
FRACTURE STIMULATED SECTION	2 km in the interval of 2973 to 2971 m (MD)
WATER AND PROPPANT VOLUMES USED	1248 m^3 of fracturing fluid / 49.871 tonnes of proppant
FLOWBACK FLUID VOLUME	372 m^3 of flowback fluid (approx. 30% of the total injected process fluids)
GAS MANAGEMENT	Flare burning

ADMINISTRATION

CONCESSION

NUMBER	70/2009/p
GEOLOGICAL TARGET	to prove crude oil and natural gas resources
VALID TILL	2017

DECISION ON ENVIRONMENTAL PRECONDITIONS FOR PROJECT IMPLEMENTATION

as of the 2009 legislation status, the project was not considered as an undertaking that potentially may have a significant effect on the environment; at concession amendment in 2011 the project (seismic survey) was attributed to projects that potentially may have a significant effect on the Natura 2000 sites;
with the decision of 15 July 2011 Regional Director for Environmental Protection in Rzeszów and with the decision of 16 August 2011 Regional Director for Environmental Protection in Lublin waived the obligation to prepare an environmental impact assessment for the project of Vibroseis-based seismic surveying

OPERATIONS PLAN

Decision by Director of District Mining Office in Lublin of 28 September 2012, ref. LUB/0234/88/12/TN, on the approval of drill site operations plan

WASTE MANAGEMENT

extractive waste management programme (drilling stage) approved by Lublin Local Assembly Speaker, decision of 7 July 2012, ref. RŚ.V.7240.68.2012.EW;
extractive waste management programme (fracturing and gas-flow testing stage) approved by Lublin Local Assembly Speaker, decision of 10 May 2013, ref. RŚ.V.7240.12.2013.EW;
permission for production of wastes other than extractive waste approved by Lublin Local Assembly Speaker, decision of 10 May 2013, ref. RŚ.V.7240.12.2013.EW and amended by Lublin Local Assembly Speaker's decision of 22 November 2013
hazardous waste management programme approved by Zamość District Head, decision of 8 November 2012, ref.: ROŚ.6223.13.7.2012

TESTS

INITIAL STATUS

baseline status: the tests started in August 2012 before the beginning of drill site development

FINAL STATUS

the second test round was delivered in October 2013, 3 months after completion of fracture stimulation
a test round was made in July 2014, twelve months after fracture stimulation

Appendix 1.6

TEST SITE DATA SHEET	ŁEBIEŃ	page 1/3

TEST SITE

name / designation	**Łebień / 6**
well / Operator	**Łebień LE-2H / Lane Energy Poland**

LOCATION

locality / commune / district / province	Rekowo / Nowa Wieś Lęborska / Lębork / Pomeranian
Concession area	Lębork

ENVIRONMENTAL CONDITIONS

GEOGRAPHIC LOCATION

meso-region (acc. to Kondracki, 2006)	Żarnowiec High Plain

TERRAIN

bottom moraine of the youngest glaciation, high plain holms separated by glacial troughs and valleys

the altitudes of the Tawęcino Holm range from 90 m in the north to 70 m in southern part, water courses flow in marginal flat bottom valleys

HYDROGRAPHY

WATERSHED: Kisewska Struga (a Łeba River tributary) watershed

THE NEAREST WATER COURSES / RESERVOIRS

name / distance from the well / direction

Kisewska Struga / 2.5 km / E

a water-filled fen / 1.3 km / SE

HYDROGEOLOGICAL CONDITIONS

MAIN COMMERCIAL AQUIFER (MCA)

stratigraphy	Q
depth to aquifer	14.5-5.6 m b.g.l.
type of water table	unconfined, locally confined
isolation from ground surface	variable thickness ranging from 3 to 20 m, in the drill site area approx. 3 m
filtration coefficient	0.000185 m/s
flow direction	S, SSE
time of seepage from the ground surface	no data
total time of inflow of potential pollutants	1500 at the most over a period of 10 years; to the drainage base (Kisewska Struga): > 30 years

TOP AQUIFER (TA) – merges with main commercial aquifer in the test site area

stratigraphy	
depth to aquifer	
type of water table	
isolation from ground surface	
filtration coefficient	
flow direction	
time of seepage from the ground surface	
total time of inflow of potential pollutants	

MAIN GROUNDWATER RESERVOIRS (MGR): Intra-moraine Salino Reservoir No. 108, NE of the drill site
Łeba River Ice Marginal Valley No. 107, S of the drill site

GEOLOGY

LOCATION: Peribaltic Syneclize, Central Łeba Elevation

The depth to crystalline bedrock (gneiss rocks) is in excess of 3000 m; a thick sedimentary caprock is composed of Cambrian, Ordovician, Silurian and Permian sediments; a sedimentary gap includes the Devonian, Carboniferous and Lower Permian through the Zechstein; the rocks of that stage are mostly claystones, mudstones sandstones; limestones, dolomites, gypsum, anydrytes and halite tend to be predominant at the top; the thickness of Silurian claystones is in the order of 2000 m; approx. 500 m thick Mesozoic formations include calcareous Triassic claystones and mudstones, Jurassic sands, sandstones and claystones, as well as Cretaceous sandstones, claystones and mudstones; they are overlain by Paleogene sediments of which thickness ranges from 70 to 200 m; on regression of the Upper Cretaceous sea, terrestrial conditions prevailed up to the Middle Eocene; another transgression occurred in the Eocene; terrestrial sediments were deposited in freshwater reservoirs in the Miocene; the profile of Quaternary sediments is reduced as a result of successive glacial exaration and meltwater erosion stages; at the drill site area, a 3-4 m thick Pleistocene sandy loam is underlain by clastic sediments of the last glaciation: varigrained sands with an admixture of gravel and infrequent pebbles.

TEST SITE DATA SHEET	ŁEBIEŃ	page 2/3

CLIMATE

region	coastal region, highly variable weather, cool summers and mild winters
average annual temperature	+7.8°C
average annual precipitations	675 mm
predominant winds	W, SW
snow cover duration	55-65 days
vegetation period duration	200-210 days

NATURE PROTECTION

area rank / name / straight line distance from the drill site / direction

Natura 2000 special bird protection area / Lębork Forests / 5.78 km / E
Natura 2000 special habitat protection area / Choczewo Lakes / 9.49 km / E, NE
Natura 2000 special habitat protection area / Łeba Marshes / 11.75 km / SW
Natura 2000 special habitat protection area / Górkowski Forest / 11.62 km / NWW
protected landscape area / Choczewsko-Saliński / 5.27 km / N-E
protected landscape area / Reda - Łeba Ice-marginal Valley / 5.41 km / S-SE
protected landscape area / a section of Reda - Łeba Ice-marginal Valley and Moraine Hills South of Lębork / 9.31 km / S
protected landscape area / Coastal / 14.65 km / N
national park / Słowiński National Park - buffer zone / 6.73 km / NW
reserve / Pużyckie Łęgi - buffer zone / 3.94 km / E
reserve / Pużyckie Łęgi / 4.02 km / E
reserve / Borkowskie Wąwozy / 9.17 km / N
reserve / Osmunda Regalis at Łęczyno / 10.16 km / E
reserve / Nowe Wicko / 10.98 km / NWW
reserve / Wielistowskie Źródliska / 1.04 km / SE
reserve / Łebskie Bagno - buffer zone / 11.55 km / SW
reserve / Wielistowskie Łęgi / 11.69 km / SE
reserve / Łebskie Bagno / 11.75 km / SW
reserve / Las Górkowski / 12.62 km / NWW
reserve / Choczewskie Cisy / 14.46 km / N

SPATIAL AND ECONOMIC CONDITIONS

NEIGHBOURHOOD

THE NEAREST COMMUNES

commune / straight line distance from the drill site

Wicko / 2.2 km	Lębork / 8.8 km
Choczewo / 3.7 km	Potęgowo / 15.8 km
Łęczyce / 2.6 km	Główczyce / 10 km

THE NEAREST BUILDINGS

locality / type of buildings / straight line distance from the drill site / direction

Karlikowo Lęborskie / dispersed farmsteads / 0.7 km / NE
Karlikowo Lęborskie / isolated buildings / 1.2 km / E
Karlikowo Lęborskie / dispersed farmsteads / 1.5 km / NE

LAND USE: mostly cropland, arable fields, pastures and meadows in immediate drill site neighbourhood;

ACCESS

PROVINCIAL ROAD

provincial road number / section national road 6 / Szczecin-Tricity

ACCESS ROADS

road category / road surface / section

from national road 6: district road / asphalted / 10.5 km
from provincial road 214 Łeba-Warlubie: district road / asphalted / 7.5 km

DEMOGRAPHY

POPULATION DENSITY

48 people / km^2

INFRASTRUCTURE

WATER SUPPLY PIPELINES	in the drill site area, households have access to a water supply system; in localities where a water supply system is unavailable the residents use privately-owned water wells
SEWERAGE SYSTEMS	In the drill site area, Obliwice and part of Łebień are equipped with sewer systems; elsewhere, domestic wastewater is stored in sealed tanks
HEAT SUPPLY	Individual heating systems, no centralized heat supply management
GAS SUPPLY NETWORK	10% of commune residents are gas supply system users

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DRILL SITE OPERATOR

PLOT OF LAND

ref. number / size	147/1 / 3.74 ha

DRILL SITE DEVELOPMENT

PRELIMINARIES	levelling, topsoil recovered and stored in earthen embankments N, S and E of drill site; sand backfill, concrete slabs
SEALING	none
DRAINAGE SYSTEM	buried, concrete tank in southern part of the drill site for storm water collected with site drainage system, the tank is located at a depth of approx. 3 m b.g.l.
PROCESS WATER TANKS	*type / quantity / capacity / footprint* earthen / 2 / 6000 m^3 + 12 000 m^3 / 1.3 ha

DRILLING OPERATIONS

MAIN CONTRACTOR	MND Drilling & Services
DURATION	May 2011 - June 2011
FINAL DEPTH	4 075 m (MD)
HORIZONTAL LEG: *length / direction*	1000 m / SSW

FRACTURE STIMULATION AND GAS-FLOW TESTS

MAIN CONTRACTOR	fracture stimulation: Schlumberger; gas-flow tests: Exalo
DURATION	fracture stimulation: 19 August 2011 - 28 August 2011; gas-flow tests: September 2011 and July 2013
FRACTURE STIMULATED SECTION	horizontal
WATER AND PROPPANT VOLUMES USED	17302.5 m^3 of fracturing fluid / 1191.07.88 tonnes of proppant data verified after 2011
FLOWBACK FLUID VOLUME	7 759.48 m^3 of fracturing fluid recovered (approx. 45% of the total injected process fluids) 2013 gas-flow test data included
GAS MANAGEMENT	Flare burning

ADMINISTRATION

CONCESSION

NUMBER	16/2007/p
GEOLOGICAL TARGET	appraisal of natural gas accumulations in Lower Silurian and Ordovician shales
VALID TILL	2016

DECISION ON ENVIRONMENTAL PRECONDITIONS FOR PROJECT IMPLEMENTATION

not required

OPERATIONS PLAN

Decision by Director of District Mining Office in Poznań of 12 April 2011, ref. ł32/0234/0001/11/02193/KM, on the approval of drill site operations plan;
Decision by Director of District Mining Office in Poznań of 9 August 2011, ref. 212/0234/0002/11/058550/NW, on the approval of supplement 1 to drill site operations plan;
Decision by Director of District Mining Office in Poznań of 19 September 2012, ref. 212/0234/0002/12/06445/KM, on the approval of supplement 2 to drill site operations plan;
Decision by Director of District Mining Office in Poznań of 17 April 2013, ref. POZ 0234.180.2013.SB/KM on the approval of supplement 3 to drill site operations plan
Decision by Director of District Mining Office in Poznań of 20 June 2013, ref. POZ 0234.356.2013.EC/KM on the approval of supplement 3 to drill site operations plan

WASTE MANAGEMENT

extractive waste management programme approved by Pomeranian Local Assembly Speaker's decision of 2 May 2011, ref. DROŚ-S.EB.7654.91.2011.EB, Land Energy Poland's statement of 28 May 2013 on the planned changes in waste management programme (under Art. 12.4 of Waste Management Act, dated 10 July 2008); hazardous waste management programme, as approved by the decision of District Head in Lębork, dated 18 April 2011, re. OŚ.6230.3.2011; Pomeranian Local Assembly Speaker's decision of 14 May 2013, ref. DROŚ-S.7243.16.2013.EB - Permission for waste production by drilling well stimulation and testing installation

TESTS

INITIAL STATUS

not applicable

FINAL STATUS

tests were made two years after well fracture stimulation operations
the results were compared with the tests made in 2011 under the project "Study on environmental aspects of hydraulic fracture stimulation of the Łebień LE-2H well"

Appendix 1.7

TEST SITE DATA SHEET	GAPOWO	page 1/3

TEST SITE

name / designation	**Gapowo / 7**
well / Operator	**Gapowo B-1/B-1A / Indiana Investments**

LOCATION

locality / commune / district / province	Gapowo / Stężyca / Kartuzy / Pomeranian
Concession area	Bytów

ENVIRONMENTAL CONDITIONS

GEOGRAPHIC LOCATION

meso-region (acc. to Kondracki, 2006)	Kaszuby Lake District

TERRAIN

a diversified landscape, numerous lakes

moraine high plain with very diversified terrain; a prominent line of frontal moraine hills; northward of the hills extends a rolling and hilly high plain, and to the south mostly flat outwash plains, slightly sloping southward;

no forests, small lakes, peat bogs and coppices add to landscape diversity; prominent landforms are glacial troughs, including the Radunia Trough with Raduńskie Górne and Stężyckie Lakes

HYDROGRAPHY

WATERSHED: Raduńskie Górne Lake

THE NEAREST WATER COURSES / RESERVOIRS

name / distance from the well / direction

Raduńskie Górne Lake / 2.5 km / SE

HYDROGEOLOGICAL CONDITIONS

MAIN COMMERCIAL AQUIFER (MCA)

stratigraphy	Q
depth to aquifer	top intra-moraine aquifer: 20-27 m b.g.l. second intra-moraine aquifer: 22-43 m b.g.l.
type of water table	confined
isolation from ground surface	top intra-moraine aquifer - complete isolation, locally no isolation the second intra-moraine aquifer - complete isolation
filtration coefficient	0.000015-0.00039 m/s
flow direction	SE
time of seepage from the ground surface	> 7 years
total time of inflow of potential pollutants	to the nearest drilled water well >30 years

TOP AQUIFER (TA)

stratigraphy	Q
depth to aquifer	2.2-15.43 m b.g.l.
type of water table	unconfined, locally confined
isolation from ground surface	locally isolated by the caprock of sandy boulder clays
filtration coefficient	no data
flow direction	SE
time of seepage from the ground surface	no data
total time of inflow of potential pollutants	no data

MAIN GROUNDWATER RESERVOIRS (MGR): Gdańsk Sub-basin No. 111, at a distance of approx. 14.5 km NE of the drill site
Gołębiewo Intra-moraine Reservoir No. 116, at a distance of approx. 18.5 km SE

GEOLOGY

LOCATION: deep buried western part of Peribaltic Syneclize

the depth to the SSW sloping crystalline bedrock ranges from 4000 m to more than 5000 m b.g.l.; Precambrian red conglomerates and arkose sandstones of the Żarnowiec Series are the oldest identified sedimentary rocks; Cambrian sediments are composed of sandstones, mudstones, claystones and marly limestones with intercalations of fine-grained siliceous quartz sandstones in total about 285 m thick; The Gapowo B-1 well penetrated Ordovician limestones and marly limestones of the Kopalino Formation, dark grey claystones with black calcareous shale layers of the Sasino Formation, dark claystones with organic matter layers and beds of marls and limestones of the Prabuty Formation, in total 50 m thick; the monotonous Silurian claystone/mudstone complex with a small admixture of carbonates in the matrix, in the form of calcareous concretions and thin layers of limestone or dolomite, is in total 2132 m thick in Gapowo B-1 well; The Silrian complex is overlain, with a huge stratigraphic gap encompassing the entire younger Paleozoic, by approx. 43 m thick Permian sandstones (Rotliegend); followed by three oldest cyclotems, including the final Permian terrigenous sediments; Mesozoic formations are much reduced with numerous stratigraphic gaps; Paleogene and Neogene sediments are grey fine-grained sands and siliceous or siliceous-carbonate sandstones (2013 m); the thicknesses of Quaternary sediments, mostly of glacial origin, are 110 to 180 m at the Tertiary elevation and more than 250 m in the Radunia Trough region.

TEST SITE DATA SHEET	GAPOWO	page 2/3

CLIMATE

region	Pomeranian Lake District
average annual temperature	+6.5°C
average annual precipitations	630 mm
predominant winds	SW, SE
snow cover duration	70-80 days
vegetation period duration	210-220 days

NATURE PROTECTION

area rank / name / straight line distance from the drill site / direction

scenic park / Kaszuby Scenic Park / 2.5 km / E, SE
protected landscape area / Gowidlino / 4.5 km / W
Natura 2000 special habitat protection area / Uroczyska Pojezierza Kaszubskiego / 2.5 km / E and 4 km / SSE
Natura 2000 special habitat protection area / Dłużnica Trough / 6 km / SE
Natura 2000 special habitat protection area / Miechowiska Sulęczyńskie / 8.5 km / W
Natura 2000 special habitat protection area / Słupia Valley / 9 km / W
Natura 2000 special habitat protection area / Chościckie Lakes / 13 km / WWN
Natura 2000 special habitat protection area / Kistowskie Lakes / 12 km / WWN
Natura 2000 special habitat protection area / Kurze Grzędy / 15.75 km / NNE
Natura 2000 special habitat protection area / Staniszewskie Błoto / 15 km / NNE
Natura 2000 special bird protection area / Mirachowskie Forests / 12 km / N
Natura 2000 special bird protection area / Słupia Valley / 12 km / S
Natura 2000 special bird protection area / Bory Tucholskie / 19 km / WNW

SPATIAL AND ECONOMIC CONDITIONS

NEIGHBOURHOOD

THE NEAREST COMMUNES

commune / straight line distance from the drill site

Sulęczyno / 0.5 km
Sierakowice / 5.5 km
Kartuzy / 10.3 km
Somonino / 13.0 km
Kościerzyna / 5.3 km

THE NEAREST BUILDINGS

locality / type of buildings / straight line distance from the drill site / direction

Klukowa Huta / densely built-up area / 0.5 km / E, SE
Reja / isolated buildings / 0.7 km / NE
Dubowo / isolated building / 0.3 km / SE
Stężycka Huta / densely built-up area/ 1.0 km / SW

LAND USE the drill site is surrounded by arable fields with cropland in immediate proximity; borders on a small forest in the north and east; sand and gravel pit "Żuromino II" (size: almost 40 ha) is located at a distance of 1.2 km towards SE

ACCESS

PROVINCIAL ROAD

provincial road number / section 214 / Łeba-Warlubie

ACCESS ROADS

road category / road surface / section ingress directly from the provincial road

DEMOGRAPHY

POPULATION DENSITY

61 people / km^2

INFRASTRUCTURE

WATER SUPPLY PIPELINES	93% of the commune residents are water supply system users
SEWERAGE SYSTEMS	a sewer system is available only in the village of Stężyca, approx. 90% of village residents are system users (approx. 20% of total population of the Commune); in other localities municipal wastewater is collected in sealed tanks
HEAT SUPPLY	Individual heating systems, no centralized heat supply management
GAS SUPPLY NETWORK	none

TEST SITE DATA SHEET	GAPOWO	page 3/3

DRILL SITE OPERATOR

PLOT OF LAND

ref. number / size	8, 9 / 3.16 ha

DRILL SITE DEVELOPMENT

PRELIMINARIES	levelling, topsoil removed, sealing sheet lining, aggregate pavement
SEALING	sheet lining over the entire drill site area
DRAINAGE SYSTEM	circular drainage ditch, drainage tank located in E part of the drill site
PROCESS WATER TANKS	*type / quantity / capacity / footprint* pool / 1 / 10000 m^3 / 0.3 ha

DRILLING OPERATIONS

MAIN CONTRACTOR	MND Drilling & Services
DURATION	January 2014 - February 2014
FINAL LENGTH / DEPTH	6058 m (MD) / 4183 m (TVD)
HORIZONTAL LEG: *length / direction*	2272 m / NE

FRACTURING OPERATIONS

MAIN CONTRACTOR	United Oilfield Services
DURATION	12 May 2014 - 14 May 2014
FRACTURE STIMULATED SECTION	the interval of 5859.8 m to 4408.9 m (MD)
WATER AND PROPPANT VOLUMES USED	26022 m^3 of fracturing fluid / 591.45 tonnes of proppant
FLOWBACK FLUID VOLUME	5899 m^3 of flowback fluid (approx. 22.67% of the total injected process fluids) recovered
GAS MANAGEMENT	Flare burning

ADMINISTRATION

CONCESSION

NUMBER	17/2010/p
GEOLOGICAL TARGET	to prove crude oil and natural gas accumulations in Lower Permian, Upper Silurian, Upper Ordovician and Middle Cambrian formations
VALID TILL	2016

DECISION ON ENVIRONMENTAL PRECONDITIONS FOR PROJECT IMPLEMENTATION

Decision by Regional Director for Environment Protection in Gdańsk of 6 March 2013
ref.: RDOŚ-Gd-WOO.4210.22.2012.ER

OPERATIONS PLAN

the decision by Director of District Mining Office in Poznań of 5 December 2013, ref. POZ0234.761.2013.EC/KM on the approval of drill site operations plan

WASTE MANAGEMENT

waste management programme approved by Pomeranian Local Assembly Speaker, decision of 28 November 2013, ref. DRO-S.7240.40.2013.EB;
Kartuzy District Head's decision of 9 March 2012, ref. R.6220.12.2011.EZ, on the award of permission for production of wastes from oil and gas exploration and appraisal operations

TESTS

INITIAL STATUS

as-found status: the vertical Gapowo B-1 well drilled in 2012; the horizontal Gapowo B-1A well drilled at the same location
the tests started in December 2013 before the beginning of horizontal well drilling

FINAL STATUS

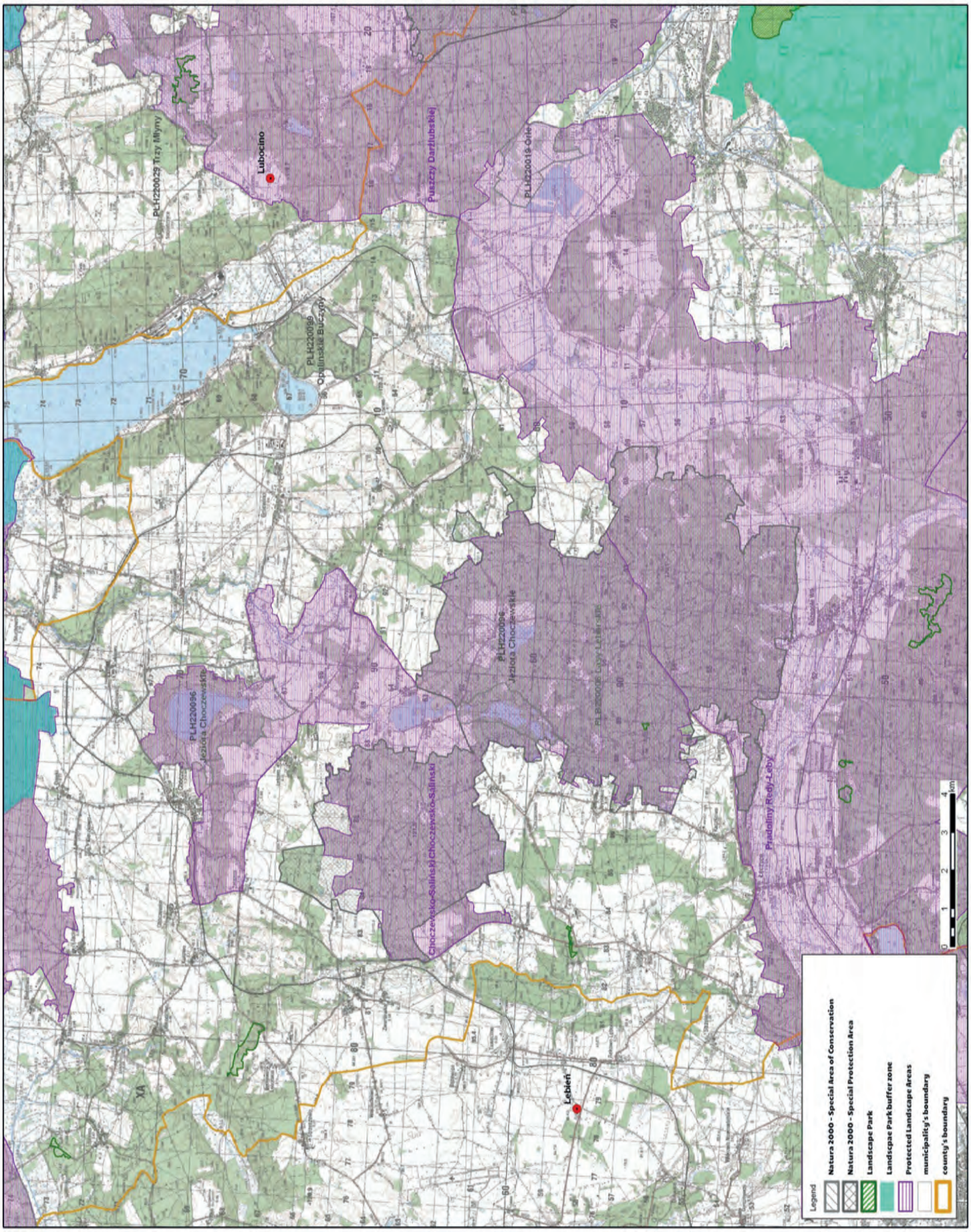
the second test round was delivered in September 2014 on completion of gas-flow tests by the Operator

Appendix 2

TEST SITE LOCATIONS WITH REGARD TO PROTECTED AREAS

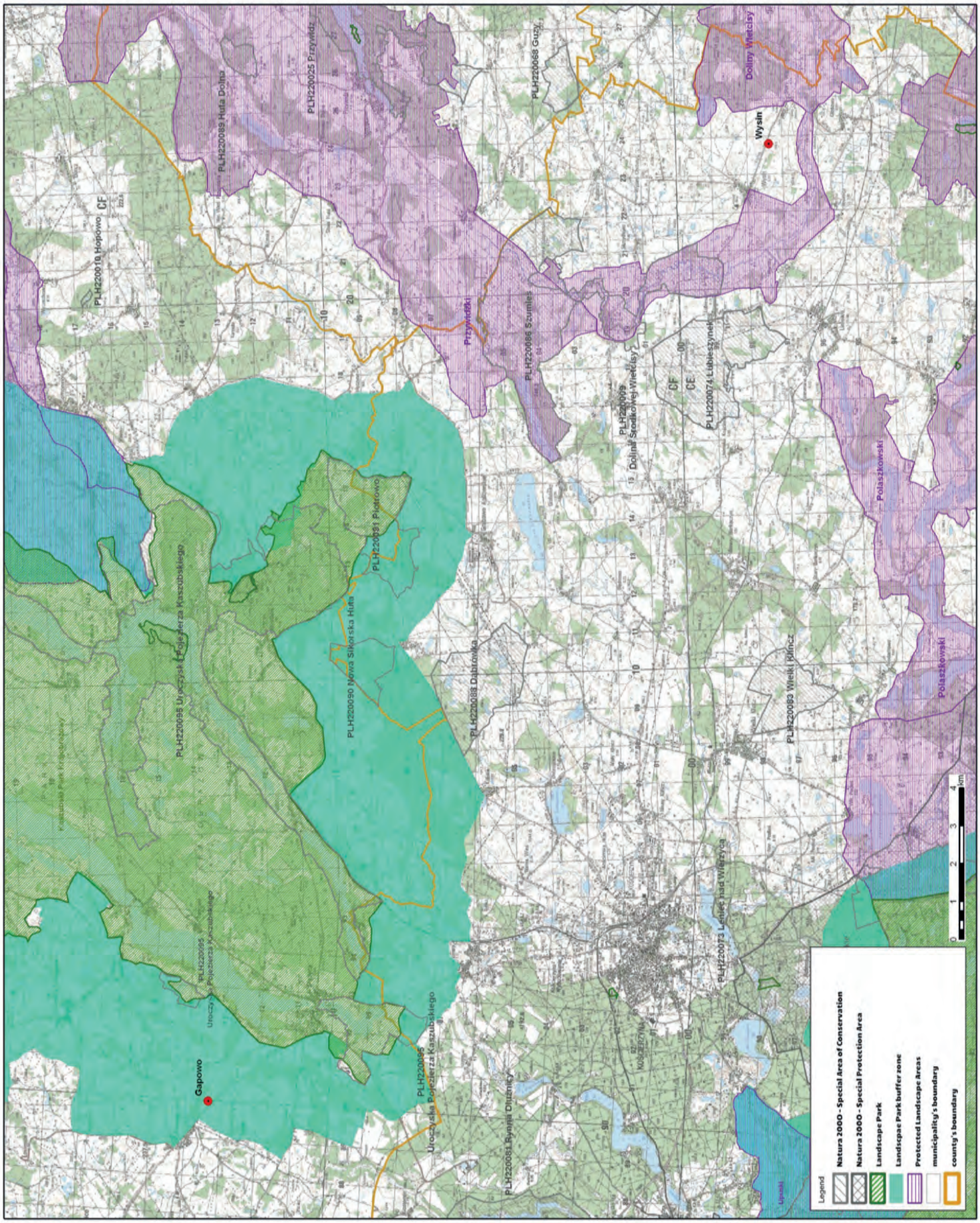
Appendix 2.1

Lubocino and Łebień test site locations with regard to protected areas



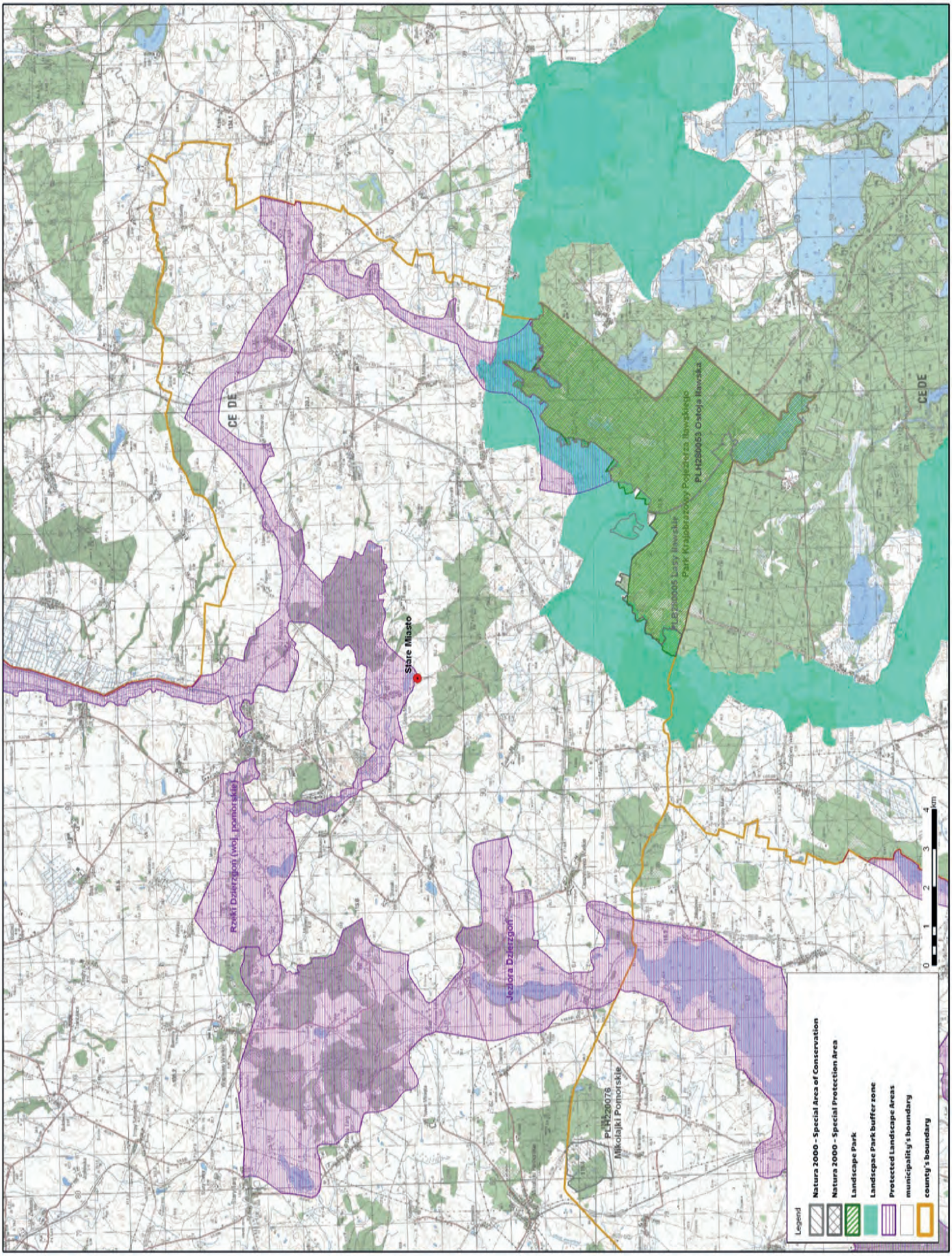
Appendix 2.2

Gapowo and Wysin test site locations with regard to protected areas



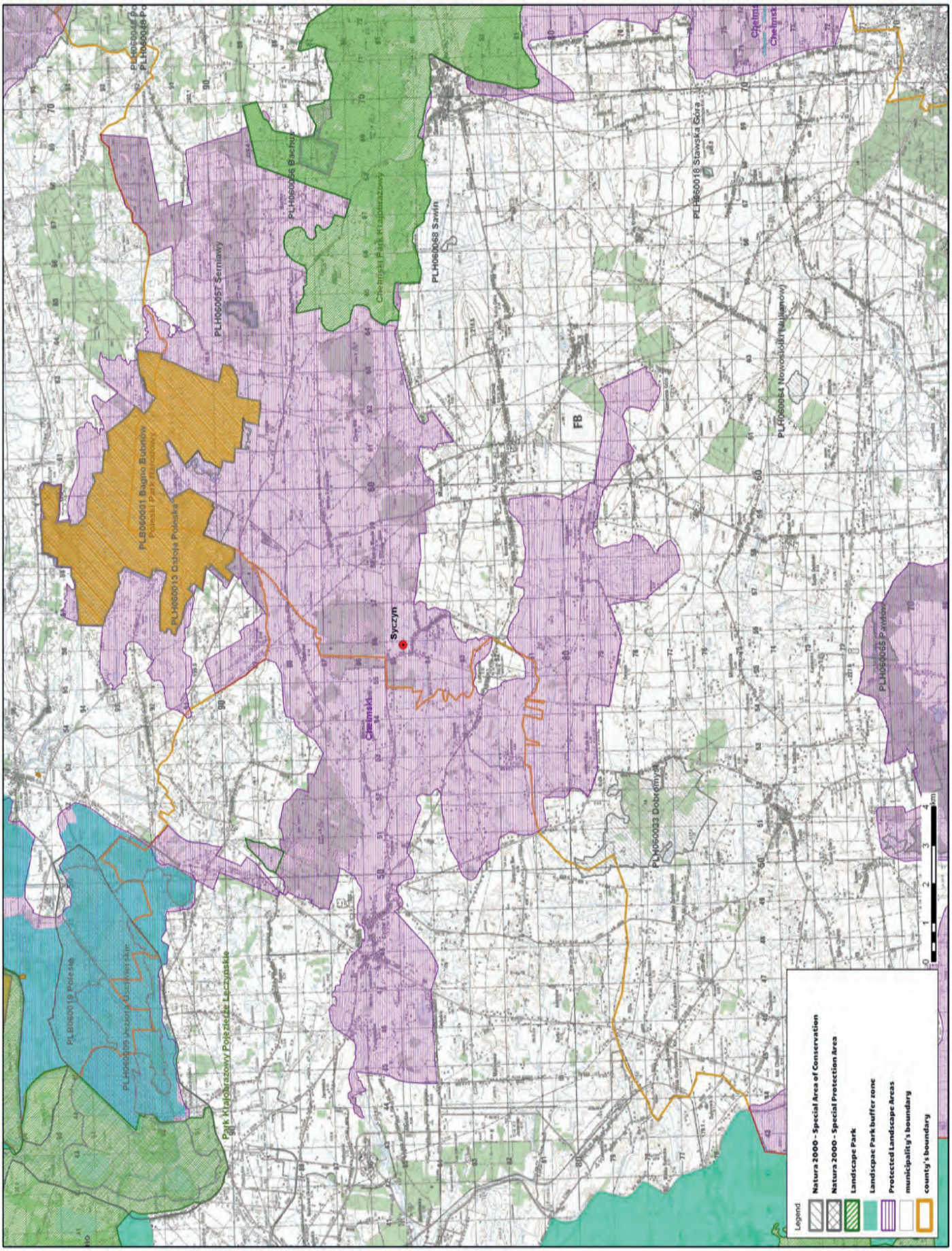
Appendix 2.3

Stare Miasto test site location with regard to protected areas



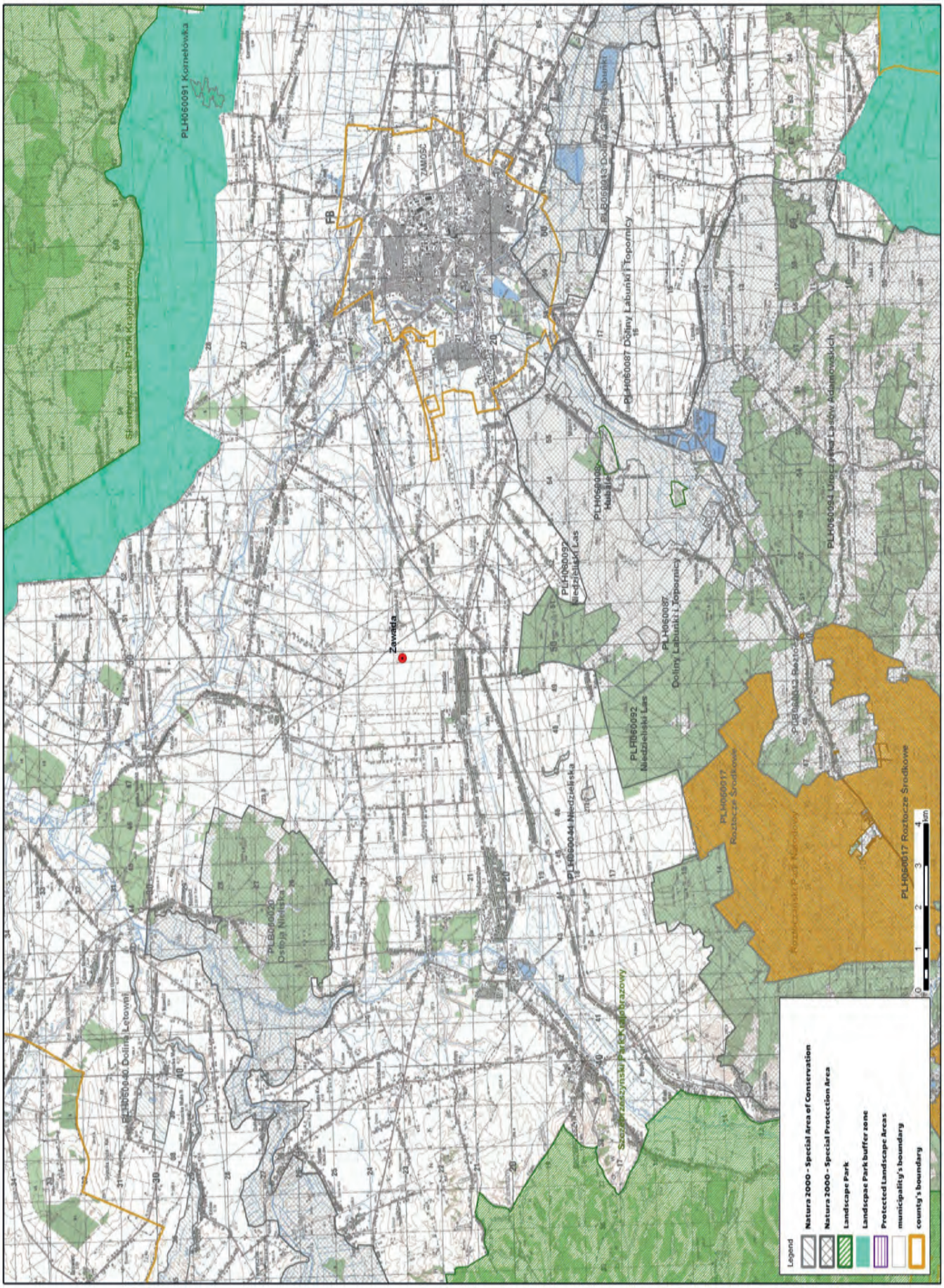
Appendix 2.4

Syczyn test site location with regard to protected areas



Appendix 2.5

Zawada test site location with regard to protected areas



Appendix 3

LIST OF POTENTIAL ENVIRONMENTAL EFFECTS OF UNCONVENTIONAL OIL AND GAS PROSPECTION AND EXPLORATION OPERATIONS

List of potential environmental effects of unconventional oil and gas prospection and exploration operations

Environmental compartment	Effect	Stage of operations – potential effects			
		Preliminaries (drill site development)	Drilling operations	Hydraulic fracture stimulation and gas-flow tests	Well abandonment and site reclamation
1	2	3	4	5	6
Ambient air	Air pollution	Exhaust gas emissions from travel and operation of vehicles and generator sets; exhaust gas emissions from vehicular traffic	Exhaust gas emissions from vehicular traffic, operation of generator sets and drilling rig, pollutant emissions from drilling crew quarters (the on-site boiler room)	Exhaust gas emissions from pump sets, vehicular traffic, reservoir gas emissions, flared gas combustion, pollutant emissions from crew quarters (the on-site boiler room)	Exhaust gas emissions from travel and operation of vehicles and generator sets; exhaust gas emissions from vehicular traffic
	Dusting	Uplift of dust from the ground at earthworks, heavy vehicular traffic on unpaved roads	Uplift of dust from the drill site yard	A heavier vehicular traffic on unpaved roads, uplift of dust from drill site yard, incidental events at proppant handling operations	Uplift of dust from the ground at earthworks, heavy vehicular traffic on unpaved roads
Ground and soil	Soil pollution	Drill site development using external (potentially polluted) soil, vehicular traffic, operation of heavy construction equipment (spills of oil products), incidental events (equipment failures)	Inadequate drill site surface protection, inexistent or inadequate drill site drainage system	Inadequate drill site surface protection, inexistent or inadequate drill site drainage system, incidental events (e.g. flowback fluid spill through the flare), improper waste handling	Vehicular traffic, heavy equipment operation (spills of oil products) incidents (equipment failures), inappropriate removal of site lining sheets (polluted soil and materials left)
	Alteration of natural soil structure by drill site facilities	Site preparation for construction, mechanical changes in the soil profile topsoil removal)			Soil restoration in the drill site area
	Deteriorated productivity of soils	Long-term action of loads on the soils- alteration of substrate compaction degree	Long-term action of loads on the soils- alteration of substrate compaction degree	Long-term action of loads on the soils- alteration of substrate compaction degree	Inadequate site reclamation
	Gas (e.g. Methane, carbon dioxide) accumulation in the soil air		Microbial fermentation in oxygen deficient environment (in the sealing sheet lined area)	Gas migration from geological formations, microbial fermentation in oxygen deficient environment (in the sealing sheet lined area)	
Groundwater	Top aquifer pollution	Heavy vehicular traffic, operation of heavy construction equipment, incidents (e.g. Oil product spills)	Inadequate drill site surface protection, inexistent or inadequate drill site drainage system, improper well construction (compromised well integrity), incidents (e.g. drilling rig failure)	Heavy vehicular traffic (oil product spills), inadequate drill site surface protection, inexistent or inadequate drill site drainage system, incidents (e.g. equipment failure), improper waste handling	Heavy vehicular traffic, heavy equipment operation (spills of oil products) incidents (equipment failures), inappropriate removal of site lining sheets (polluted soil and materials left)
	Pollution of commercial aquifers	Heavy vehicular traffic, operation of heavy construction equipment, incidents (e.g. Oil product spills)	Insufficient knowledge of local geology, improper well construction, wrong drilling parameters, inadequate drill site surface protection, inexistent or inadequate drill site drainage, incidents (e.g. drilling rig failure)	Inadequate drill site protection, compromised well integrity (fracturing fluid or gas migration), inexistent or inadequate drill site drainage, improper waste handling	Improper well abandonment
	Pollution of deep aquifers		Insufficient knowledge of local geology, improper well construction, wrong drilling parameters	Reactivation of local transmissive fault zones, compromised well integrity (fracturing fluid or gas migration)	Improper well abandonment
	Commingling of aquifers		Insufficient knowledge of local geology, improper well construction, wrong drilling parameters		Improper well abandonment
	Depleted groundwater reserves			Water withdrawal for fracturing fluid preparation	

1	2	3	4	5	6
Surface waters	Surface water pollution	Heavy vehicular traffic, runoff from drill site area, incidents (e.g. oil product spills)	Flow of polluted groundwater to surface waters, run-off from drill site area	Flow of polluted groundwater to surface waters, run-off from drill site area, improper waste handling	Runoff from drill site area
	Depletion of resources			Water withdrawal for fracturing fluid preparation	
Terrain and landscape	Terrain alterations	Site preparation for pad development			Initial terrain features not restored
	Landscape changes	Change in intended land use and development	Changes in land use patters at the drill site area (e.g. derrick placement)	Changes in land use patters at the drill site area	
	Landscape changes	Seismic surveying, operation of equipment and heavy vehicles, heavy vehicular traffic			
Other	Noise nuisance	Seismic surveying, heavy vehicular traffic, operation of heavy construction equipment	Operation of drilling rig, generator sets, pumps, compressors, fans, etc., vehicular traffic	Heavy vehicular traffic, short-term but intense operation of pump sets, mixers, etc. at fracturing fluid injection, operation of generator sets	Heavy vehicular traffic, operation of heavy equipment and generator sets
	Vibrations and induced earthquakes	Heavy vehicular traffic	Heavy vehicular traffic	Well perforation and fracturing fluid injection, a heavier vehicular traffic	
	Waste management problems		Production, storage, transport and neutralisation/recycling of extractive wastes: cuttings, spent mud and wastes from day-to-day upkeep, service and maintenance of machinery and equipment	Production, storage, transport and neutralisation/recycling of extractive wastes: flowback fluid and wastes from day-to-day upkeep, service and maintenance of machinery and equipment	Production, storage, transport and neutralisation/recycling of wastes, e.g. geomembrane elements, PEHD sheets, contaminated concrete slabs