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**THREATS TO THE ENVIRONMENT
IN THE AREAS OF ABANDONED EXTRACTION
OF HYDROCARBON DEPOSITS****

1. INTRODUCTION

Environmental impact of mining is not limited to exploration and extraction deposits but has some future implications. In the former area of hydrocarbons extraction are contaminations coming from past extraction processes and problems relating to the abandonment of wells and deposits. The influence varies depending on the geology, topography, climate and on other factors in the mining areas. The source of contamination in the mining area are, e.g. improper disposal of some of the large volumes of saline water, hydrocarbon and produced water releases caused by equipment failures, vandalism, flooding, and accidents and leakage from an abandoned gas well and/or disturbance of rock formation during the drilling. The main environmental aspect of abandonment extraction of hydrocarbon deposits is connected with natural processes on the deposit and anthropogenic aspect, like abandoned wells. The main objectives of this work is to discuss the main environmental problems relating to abandoned hydrocarbon deposits and some technological aspects.

**2. IMPROPER DISPOSAL OF LARGE VOLUMES
OF PRODUCED SALINE WATER**

Experience from many countries showed that petroleum production, drilling operations, and improperly sealed abandoned wells have caused major contamination of surface

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** The research leading to these results has received funding from the Polish-Norwegian research programme operated by the national centre for research and development under the norwegian financial mechanism 2009–2014 in the frame of project contract No. Pol-Nor/235294/99/2014

and ground waters and soils [17, 20, 21, 37]. Contamination mainly results from the improper disposal of large volumes of the produced saline water with oil and gas, and from hydrocarbon and produced water releases due to equipment failures, vandalism, flooding, and accidents. Oil and gas industry generate the largest stream of waste in the form of water, a by-product of drilling. Large volumes of wastewater in the form of brine which usually accompanies oil and gas production. Oil-bearing formations usually contain altered seawater trapped in sediment pores. Usually, the brine to oil and gas ratio is at least 2 to 1 in traditional oil wells, but larger proportions are also common. Typically the amount of produced brine increases when the quantity of recoverable oil is reduced [39]. This problem of saline water can be better understood if we analyze the transport infrastructure and natural attenuation of inorganic salts, trace metals, organic compounds and radionuclides present in produced water. In some mining area the production of brine is the major potential environmental contamination hazard associated with oil and gas production. The example of it could be Williston Basin [16].

The contaminations can last for a long time after the extraction process is ended, therefore this problem refers to the areas of abandoned deposits. The results of analyses of some oil field areas like the Osage County, Oklahoma [22] show that the salts have essentially been removed from the sandy soil, but degraded and weathered oil persists on the surface of old oil and brine pits, close to sites of old tanks, on old channels that carried oil from tanks to the oil pits, and other impacted areas. Significant amounts of salts from produced-water releases and petroleum hydrocarbons still remain in the soils and rocks of the impacted area after more than 60 years of natural attenuation. Significant amounts of produced water may percolate into the superficial rocks and flow towards the reservoir. The chemical composition of released brines could be modified further by sorption, mineral precipitation/dissolution, transpiration, volatilization and bacterially mediated oxidation/reduction reactions.

Oilfield brine has also contaminated many of the world's aquifers. High chloride concentrations commonly characterize oilfield pollution of groundwater. On average, brine contains 50 000 mg L⁻¹ chloride, which, along with other constituents of brine, can be toxic to crops, corrosive to metal, and unsafe to drink. Historically, oilfield brine has been dumped into pits and gullies, and sprayed onto roads. Presently most oilfield brine in the U.S. is injected into deep disposal wells. Both past and present brine disposal practices can contaminate groundwater [19].

The consequence of brine contamination to biotic communities could be highly variable. There are many factors on which it depends, e.g. relative amount of brine introduced to the system, background salt type and concentration, the composition of the biota, and the relation between the nature and groundwater (recharge, flow through, discharge) [16].

3. DECOMMISSIONING OF WELLS AND ITS INFLUENCE ON THE DEPOSIT AND SURFACE CONDITIONS

Wells are closed when the extraction is over, e.g. when the oil or gas production decreases beyond the profitability threshold or drilling ends up in a dry well. Another cause

may be a technical failure during drilling, as a consequence of which further works cannot be realized, or the investor plans are changed. Prior to the closing operations a technical plan of liquidation has to be worked out. The plan is drafted on the basis of a detailed analysis of geological-technological conditions, accounting for all possible difficulties, e.g. complicated field conditions or gas exhalations around the boreholes. The closing operations lie in the removal of the top part of wellheads and filling of the well space with silt or mud and cement plugs. Thus protected well is labeled and the area around it is reclaimed and restored.

The first to be liquidated are wells sited on deposits which to be abandoned or depleted, which may create environmental hazard due to the uncontrollable outflows of hydrocarbons or fire and explosion hazard. Then uneconomic and low productivity wells are closed.

The process of well liquidation requires a specific approach also with regard to local society and natural environment. This refers to wells drilled with percussion method in the SE Poland. In many cases the well has to be overworked prior to secondary liquidation. The works should follow uniform methodics, accounting for qualification criteria and conditions to be met by wells to be closed. According to the authors, the liquidation method should be so selected as to provide a tight insulation to the drilled water-, oil- and gas-bearing horizons to eliminate potential gas escapes to the surface.

The wells should be realized with the use of materials adjusted to the existing geologic, reservoir and technical conditions. In the presence of the existing or potential environmental impact on water, oil and gas, the well should be overworked before closing. The liquidation of the surface infrastructure of onshore wells should be preceded by:

- analysis of surface hardware of wells,
- assigning wells to a definite group of criteria deciding about the removal of the surface equipment and cutting of the surface part of the casing (to 2.5 m);
- planning well liquidation on the basis of a detailed analysis of geological-technical conditions in the well.

The closing operations are the final stage of well's life and are connected with the removal of the surface part of wellheads to about 2.5 m of depth and reclamation of the terrain. Nonetheless, even at this stage unexpected phenomena may take place in the well and its neighborhood at any time. Therefore, a base flange should be mounted on the column of production or intermediate casing to give an access in break-down situations.

The wells are selected for closing on the basis of a technical analysis and local inspections. The following groups of wells designed for liquidation were distinguished:

1. wells to be completely closed,
2. wells to be closed temporarily,
3. depleted wells, localized at a certain distance from the mining center, where the control is hindered, and environmental hazard covers:
 - uncontrollable outflows of hydrocarbons,
 - fire and explosion hazard.

3.1. Problems encountered while decommissioning wells

Problems encountered during liquidation of wells can be split into three groups:

- difficult field conditions of wells to be closed;
- gaseous exhalations around the already liquidated wells;
- inefficient liquidation of wells.

Difficult field conditions

Areas covered by wells especially in the Carpathian forefield and the Carpathians considerably vary in character. There have been observed big height differences ranging from 200 to 300 m. Part of the area can be used for agricultural purposes, and the remaining one is grown with forests. Most of the mining areas are occupied by farm objects and in some cases also city objects. Such conditions create problems as the workover and liquidation of wells necessitate infrastructure for heavier equipment than the one already installed and used in situ. These devices are needed for the removal and driving of production pipes. When the roads are not passable, the pipes cannot be cut off and the annular space is filled with special slurries. This is a complex operation because of the limited access to the annulus. In many cases only brine is injected there. It should be emphasized that cutting off the casing and plugging of the cut space gives the highest warranty of success.

Gaseous exhalations around liquidated wells

Gaseous exhalations around the oil and gas wells are a frequent phenomenon in the area of the Carpathian forefield and the Carpathians in SE Poland. This phenomenon results from a complicated geological build and frequently weak or no cementing of the casing. Gaseous exhalations are frequently observed at a certain distance from the well axis (tens of meters), thus creating hazard for the life and health of people and environment. This problem becomes even more important when the production is stopped and the deposit is liquidated. The most common cause of gaseous exhalations in the neighborhood of closed wells is their inefficient liquidation.

Inefficient liquidation of wells

The exploitation of liquid deposits in the mining areas of the SE Poland has been realized since the close of the 19th century. A number of wells were drilled with the percussion method over some tens of years. In this technology of drilling the casing pipes remained uncemented. The diameter of the drilled well was slightly bigger than the diameter of the casing which was introduced gradually after the drill. The rock mass naturally used to contract on the casing providing tightness to the casing/rock system. In the course of liquidation of such wells attempts are made at recovering some of the casing pipes. Now the seepages of oil-products are observed to appear around some of these well evidencing the inefficiency or lack of the closing procedure. There are fragmentary records of

documentation in the form of “Geological liquidation plans”, on the basis of which we can partially recover the technical state of the wells. There are no reports evidencing the completion of the closing works. Bearing in mind the presently observed leakages we may assume that the wells had not been liquidated or the operation was inefficient, therefore should undergo secondary liquidation.

4. FLUIDS AND SEALING MIXTURES USED FOR LIQUIDATING WELLS

A variety of fluids and liquids are used in the process of well liquidation for filling the space between cement plugs. Their aim is to balance the hydrostatic and formation pressures. They should also seal the casing when it loses its tightness. Accordingly, the fluids should have the following properties:

- Very high thixotropic properties.
- No stratification into water and solid fraction.
- No toxicity.
- Lack of corrosiveness to the casing.
- Hostile to bacterial development.
- Resistant to aging in well temperature conditions.
- Ability to repress on the zones of reservoir rocks.

Sealing slurries in the form of bentonite muds («silty milk») were used for liquidating wells drilled with the percussion method. A considerable number of wells drilled with this technique were liquidated with silt. Silt balls were transported to the well with a special ladle and then a clayey mud was introduced. After making a ten or so meter thick plug the material was tamped. This gave a potentially good sealing for the reservoir layer and the layers above. The annular space between the casing was filled with high-density clayey mud. Apart from clayey plugs, some parts of the well were cemented. These were fragments of a well passing through the rocks of relatively low water content, where cement and water could be successfully bounded.

The correct liquidation of a well is conditioned by the sealing of absorptive zones in the uncased section. For doing so, the well should be passable in the absorptive zone and the hydrostatic equilibrium of the mud stabilized prior to performing cement or clayey plugs. The liquidated wells frequently open up absorptive zones of much lower pressures as compared to the hydrostatic pressure of the fluid (mud, brine) in the well. In this situation making of a cement plug in an absorptive zone is inefficient as the cement slurry will penetrate the zone and mix up with reservoir water, which in most cases consequently leads to the lack of sealing. Liquidation of absorptive zones is realized by adding special sealing materials to:

- cement slurry, or
- drilling mud.

Liquidation process of a well is followed by working out a documentation which should be submitted with the respective concession office. In the case of hydrocarbon prospecting and production this is the Ministry of Environmental Protection. The documentation reporting on the well liquidation consists of the text and graphics. The text comprises information about the date when the well was drilled and the way in which it was used, date of the beginning and end of liquidation works and the closing method.

The graphical part consists of a map with localization of the liquidated well, location-height plan and geological profile, where the type of rig, diameters, depth of casing, etc. should be indicated.

4.1. Consequences of a badly decommissioned well

The performed well connects many crustal layers. It is important at the stage of drilling to tightly insulate fresh water layers so that the natural water table is not lowered. The drilling techniques and technologies have evolved over the years. The first wells were drilled manually (dug or drilled with simple percussion tools). Then the line technology was developed and this type of drilling was popular by the 1970s. Percussion drilling was substituted with rotary drilling.

Generally, the casing was not cemented in wells drilled with the percussion method. The tightness of the well lied in the fact that the diameter of the drill bit was slightly bigger than the outer diameter of the casing and the rock mass spontaneously contracted on the pipes. From the bottom the well was sealed by a «shoe» screwed to the casing and tamped to the bottom of the well. Frequently after drilling a section of the well with a casing column, the hole was filled with silt on a special ladle, where the casing was set.

This drilling technique sometimes results in uncontrollable gas (and to a less degree oil) leakages at the production stage or after it has been closed. There are known cases when the rock mass was gassed at small depths (Borislav, Ukraine and Przeworsk). Gas is liberated in an uncontrollable manner as a consequence of which the inhabitants living in the area cannot use cellars. In such situations shallow wells can be drilled and the gas recovered or a depression can be evoked in the existing wells through the installation and casing pipes operation. The uncontrollable movement of reservoir fluids in old wells was favored by the oil pumping technology which used to be applied for a certain time. This technology lied in driving casing to a special piston on a string with a valve inside. Depression on the rocks was generated by the quick driving operations, which due to the existing untightnesses in the annular space could cause uncontrollable movements of water, oil or gas.

Another hazard related with the badly closed wells is the brine which may contaminate fresh water. Saline waters are pumped out by gas migrating to the surface or oil products liberated from the closed oil horizons through untightnesses. This problem is encountered in many areas all over the world where hydrocarbons are produced.

One badly liquidated oil well may bring about fresh water losses to the lower strata and the subsequent lowering of the natural level of fresh water over a considerable area.

In the rotary method the casing is cemented. If the operation is performed correctly, the annular space is tight.

The tightness depends on the accuracy of the cementing job. The casing should be well bounded with the rock mass.

In practice some unfavorable phenomena may accompany cementing jobs:

- in rotary drilling the well wall may be covered with mud cake, hindering (or blocking) good cementing of the casing with the source rock;
- too fast cementing may lead to incomplete displacement of mud from the annulus leaving it in various parts of the annular space in the well (mud channeling effect),
- too slow cementing job may lead to cement pumicing (especially in gas wells).

The bad state of cement may result in gaseous exhalations on the surface or in the porous and permeable strata lying on small depths.

In an extreme case, which could be observed in Poland many years ago, the terrain was elevated due to the presence of large quantities of gas in loose sand tens of meters below the surface. Then followed an uncontrollable gas eruption, inflammation, fire and subsidence of terrain burying the entire well casing. Providing good tightness of a commissioned well is significant when carbon dioxide and hydrogen sulfide are present in the natural gas or oil. These two gases are hydrate-forming and strongly corrosive. They form carbonic acid and hydrogen sulfide acid and toxic acids (hydrogen sulfide). In such wells the casing undergoes chemical corrosion, especially when the pipes are made of steel which is not resistant to acids. Liberation of above mentioned gases to the surface is very dangerous for people and natural environment.

Another issue is the liquidation of off-shore wells. In such situations the well should maintain very good tightness before uncontrollable oil and gas escapes to sea water at the stage of drilling, extracting, closing and afterwards. This would lead to immense ecological catastrophes. An exemplary liquidation of an oil well drilled off-shore is presented in Figure 1.

The analysis of Figure 1 reveals that the reservoir part can be closed with a special packer at a distance of 100 to 200 m. A cement plug about 50 m thick is disposed over the packer and then the well is filled with heavy mud. Another plug ca. 50 m thick is performed close to the borehole outlet. Its top should be about 50 m below the seabed level. A high-pressure liquidation wellhead in the form of a flange fixed to the casing is mounted about 3.5 m above the seabed. For better safety, the number of cement plugs can be increased, depending on the depth of well and hydrostatic pressure at the depth of the productive horizon. An exemplary liquidation of a well is presented in Figure 2 where part of the deposit is completely cemented and cement plugs (separated with heavy mud) are added on the well's length. This method can be used for liquidating on- and off-shore wells.

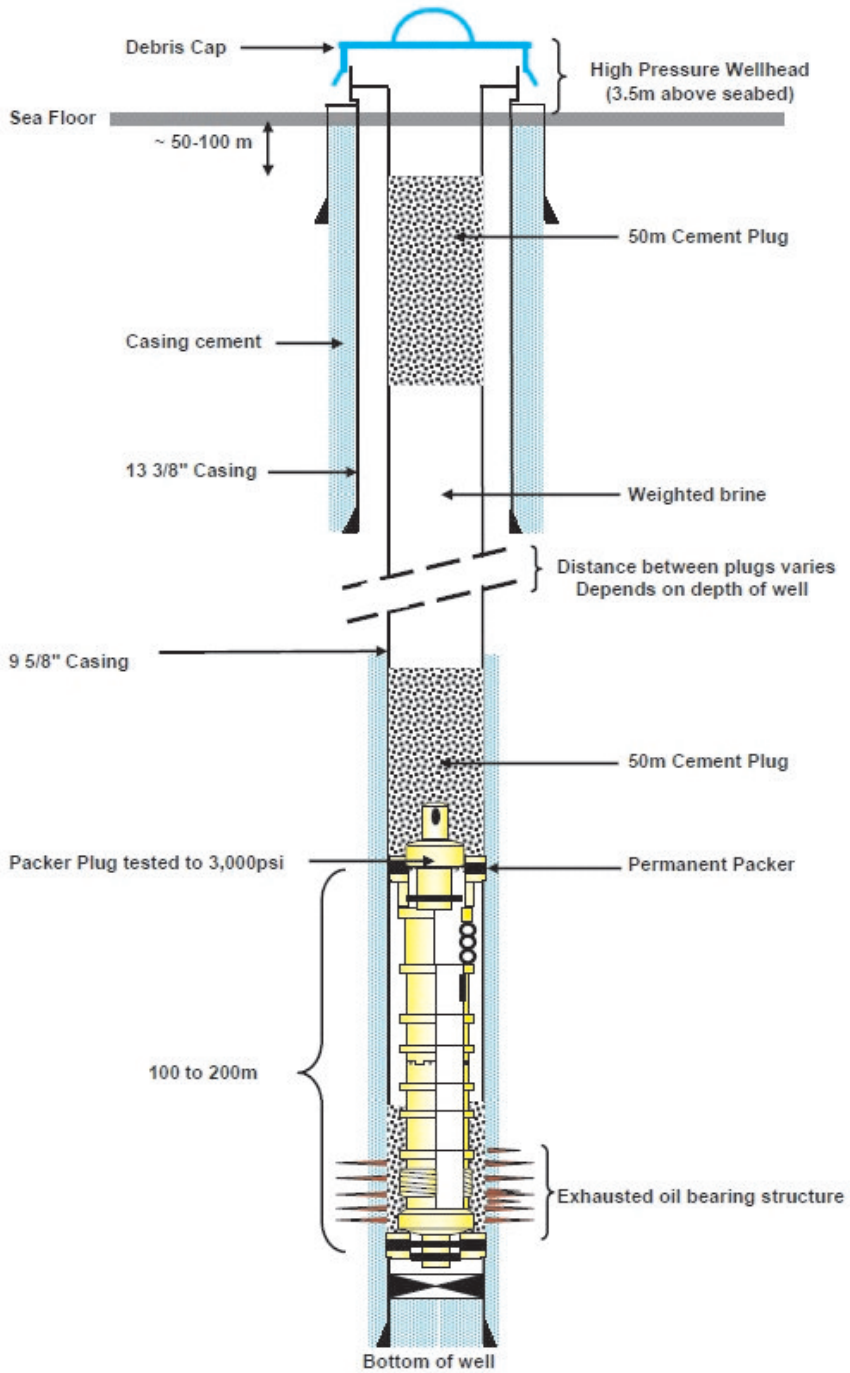


Fig. 1. Schematic of liquidation of an off-shore well [44]

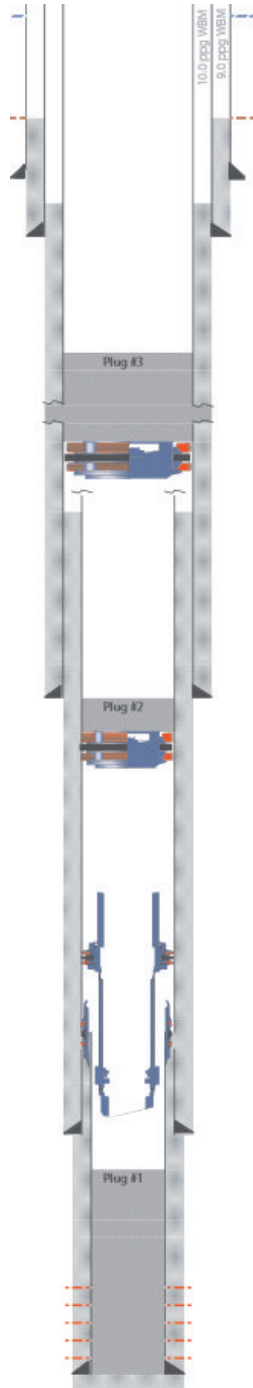


Fig. 2. Exemplary liquidation of a well with cemented reservoir layer [45]

5. ABANDONED GAS AND OIL WELLS AS A REASON OF ENVIRONMENTAL POLLUTION

Results from literature studies [35] suggest that the most probable reason for the observed pollution of the near-surface soil/aquatic environment is leakage from an abandoned gas well and/or disturbance of rock formation during the drilling. Unplugged or improperly sealed wells can result in stray gas migration [33] or contamination of shallow aquifers from brine located in deep producing zones [7]. According to Sechman et al. [35] well leakages may be divided into two categories: primary and secondary. The primary leakages are results of improper drilling and/or cementing of the casing [24, 26]. The secondary leakages may come out during the operation of producing well and are usually the effect of cement and casing [6, 10].

In the Polish and Ukrainian Carpathians it is possible to come across some areas with natural leakages of oil and natural gas emissions. The hydrocarbon mining has long historical tradition. In 1885 the first national and foreign oil companies were established on the Polish and Ukrainian territories. The war and the depletion of hydrocarbon resources caused that many deposits ceased to be extracted, e.g. Polana deposit, Figures 3–5. The present economic situation based on the use of energy minerals, creates favorable conditions for bringing back Carpathian fields to production. There are a few hydrocarbon deposits, where extraction was ended long time ago and yet the place of the wells can be seen even today. Some wells are plugged.

5.1. The environmental risk relating to restoration of formation pressure

The ended extraction may create another problem associated with the restoration of formation pressure. The gas getting to the near-surface area could be the reason of uncontrollable discharge of hydrocarbons to the environment. The state of an abandoned well before, during and after self-acting outflow of oil-polluted water is illustrated in Figures 3–5.



Fig. 3. State of abandoned well before self-acting outflow of oil-polluted water (phot. B. Winid, T. Solecki)



Fig. 4. State of abandoned well during self-acting outflow of oil-polluted water (phot. B. Winid, T. Solecki)



Fig. 5. State of abandoned well after self-acting outflow of oil-polluted water (phot. B. Winid, T. Solecki)

The blowout of hydrocarbon or brine with hydrocarbons could contaminate the aquatic environment (Fig. 6).



Fig. 6. Water surface water pollution by oil spills
(phot. B. Winid, T. Solecki)

Apart from accidental outflow of oil-polluted water the hydrocarbon leakages have been seen in the abandonment mining area. Methane which is released into the air could be a source of explosive blowing. The methane emission could cause fire hazard. Even if its release into the air does not cause any accident it is responsible for the greenhouse effect and the resulting negative environmental impact.

5.2. The risk of contamination of surface waters and groundwaters

The increased oil production, transportation and storage have led to more numerous accidental spillages, which can give rise to surface and groundwater contamination. The problem will be most acute in unconfined aquifers, particularly those in exposed geological formations. Accidental releases of crude oil and its refined products is one of the most common sources of groundwater pollution [1].

The mining regions, which are in the aquifer recharge area, should be of particular environmental concern. The leakages and blowouts of hydrocarbons could contaminate surface and groundwaters. Water could be polluted by toxic substances (hydrocarbons, metals and others) and by saline water. All these substances may create problems when working out water supply plans. The reason for this may be the presence of some elements in water composition which exclude waters from public use; such elements like sodium, chloride make such waters hard to treat. The problems with water treatments processes could depend on surface water flow. Low water level is usually connected with poor quality of water. The climate and the season of the year will have influence on water quality.

Excluding water from public use and improving the water treatment system may cause local water supply problems. Both surface and groundwaters contaminations may negatively influence on the ecosystem.

Climate changes observed in recent years give rise to a growing number of extreme weather conditions (droughts, floods, torrential rains). Due to predicted climate changes [42] two different scenarios have been created for the mobilization of pollutants and microbial processes in aquatic environment. They have been identified for the contrasting hydrological conditions: (i) the mobilization of pollutants under high flow and a relatively higher probability of biodegradation; (ii) the accumulation of pollutants during low flow and lower probability of biodegradation. Results from [42] reveal that a multiple approach for the assessment of chemical and microbiological dynamics at the streambed level has to be considered for an appropriate water resource exploitation and a more realistic prevision of the impact of pollutants in temporary aquatic environments.

In the studies conducted by Teng et al. [36] in the Songyuan oilfield, (Northeast China) the distribution of the total petroleum hydrocarbons (TPH) was investigated in groundwater and soil. The TPH were detected in most collected samples both in confined and unconfined aquifers. The differences between land-use types suggested that some abandoned oil wells or oil pits were found to be sources of contamination for groundwater. Polluted surface water and polluted soil could lead to the unconfined aquifer contamination, while the injection wells leakage and left open hole wells might be largely responsible for confined aquifer pollution. The results showed that oil leakage and losses were possibly the main reason of TPH present in soil [36].

The range of contamination depends on the subsurface lateral and vertical movement of petroleum products (including hydrocarbons). There are some other factors like: the nature of the groundwater system (particularly its vulnerability) and the quantity and physical and chemical properties of the petroleum products discharged. When the volume of the discharge is small relative to the surface area of spill, or the unsaturated zone is thick and the permeability low, a petroleum plume could be immobilised in the unsaturated zone above the water table. In that case vertical migration will be stemmed on reaching impermeable strata or when the threshold of residual saturation is attained. Discharged petroleum products will often get to the capillary fringe and then form a thin film on the groundwater table. Though emulsions will sink to different levels within the aquifer. The groundwater gradient will determine lateral pollution migration caused by hydrodynamic dispersion [40]. In the area of ended exploitation in the vicinity of abandoned wells surface water leakage from soil could contaminate surface water.

5.3. The impact on ecosystem

The hydrocarbon exploitation may have impact on ecosystem due to: human being, exploitation processes and other anthropogenic activities connected with mining operations.

The mining infrastructure may cause a risk to the ecosystem. Pad or road construction can result in the filling in or increased sedimentation of natural surface. The extended road

networks can disturb migration routes and fragment habitat critical to a multitude of species including ungulates, grassland-dependent birds, and predators. Increased traffic is a risk of vehicle collisions with all manner of wildlife, from small rodents, amphibians, snakes, and birds to large ungulates and predators. The impact on wildlife is connected with the increased disturbance and human presence particularly during vulnerable times of the year such as nesting, calving, and winter [11, 18]. The differences in ionic composition and salinity between brines and natural surface water in mining areas may have impact on the ecosystem. Elevated chloride levels could result in changing from relatively diverse freshwater plant and invertebrate communities to less diverse, salt-tolerant communities [14, 16]. Such a modification could reduce the habitat quality for natural wildlife. Additionally, altered water chemistry or elevated salinity could make mining area unsuitable for other wildlife [31].

In the reclamations phase or in other agriculture processes high NaCl concentrations can decrease the germination of salt-tolerant plants [4], and increased sodicity can affect soil structure, thus impairing plant growth [14].

The air, soil and water pollutions connected with hydrocarbon exploitation have raised major environmental concerns. The environmental effects are connected with factors of exploitation. The presence of high concentration in contaminants such as polycyclic aromatic hydrocarbons (PAHs) and naphthenic acids (NAs) in oil sands process-affected water (OSPW) may cause a risk for ecosystem due to genotoxicity. Some compounds of crude oil are carcinogenic. The studies of the genotoxic impact of OSPW-related compounds such as NAs and PAHs in a salmon species in aquatic environment of oil sands extraction along the Athabasca River (Alberta, Canada) have been conducted by Lacaze et al. [25]. The study has shown, that genotoxicity was observed in hepatocytes exposed to several NAs, mixture of them, OSPW and OSLW extracts. Among the NAs tested, the most cyclic NA was the most genotoxic [25].

There have been some investigations of the toxicity of produced waters to organisms associated with aquatic ecosystems in other oil and gas producing areas. Brines were found to be toxic to the salt-tolerant fishes sheepshead minnow (*Cyprinodon variegatus*) [5], and freshwater water flea (*Ceriodaphnia dubia*) [3]. The other example could be identified non-lethal effects, such as reduced liver weight, to western sandpipers (*Calidris mauri*) that were attributed to chronic exposure to brine in Texas [32].

5.4. Public health hazard

Each of above discussed environmental problems could have influence on the humans. The risk of gas blowouts in wells could be dangerous for people in the vicinity of this accident. Hydrocarbons present in hydrocarbon exploitation areas could directly pose a health risk to humans or contaminate plants and animals. Carcinogenic compounds of hydrocarbon contaminates are of particular concern. Absorbed by soil and then transferred to man through the food chain they could pose a risk for the human health. The contamination of surface and groundwater via leaching of nondegradable compounds and stormwater runoffs

could decrease its quality. The pollutions of agricultural areas could spoil the grass, vegetable, crops and then have impact on the cattle. All of these things are connected with the risk of contaminating food and poor quality of water.

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