Ilinykh et al.
Sustainable Environment Research (2023) 33:9
https://doi.org/10.1186/s42834-023-00171-0

Sustainable Environment Research

RESEARCH **Open Access**

A life cycle assessment of drilling waste management: a case study of oil and gas condensate field in the north of western Siberia, Russia

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Abstract

Oil production is currently impossible without drilling wells, so millions of tons of drilling waste contaminated with oil, chlorides, and heavy metals are generated every year in Russia alone. This article presents the results of a comparative life cycle assessment of water-based drill cuttings management technologies applied in Russia, including disposal, solidification, and reinjection. Life cycle assessment of the drilling waste management was performed using Open-LCA software, Ecoinvent 3.8 database and ReCiPe Midpoint (H) impact assessment method. Fossil depletion, climate change and human toxicity were chosen as impact categories. Data from oil producing companies on the composition of drilling waste and information from drilling waste treatment companies on the technologies and reagents used were also applied. To compare alternative technologies the following scenarios were compared: Scenario 0 «Landspraying», scenario 1 «Disposal», scenario 2 «Solidification» (scenario 2a – in a waste pit, scenario 2b – without a waste pit), and scenario 3 «Reinjection». Sensitivity analysis was performed to test for variations in results for oilfields located in different regions and for differences in mass of reagents used. The environmental impact of scenario 0 (landspraying) depends mostly on drilling waste composition, which is largely determined by human toxicity that can differ from 17 up to 2642 kg 1,4-DCB-eq per 1 t of drill cuttings, when for other scenarios it is from 24 up to 73 kg 1,4-DCB-eq per 1 t of drill cuttings. It means, that drilling waste landspraying is the best option only if the level of pollutants in the waste is very low. Among the other scenarios of drill cuttings management aimed at isolating pollutants from the environment, solidification technologies have the greatest environmental impact, primarily due to their use of binders. Among all scenarios, 2a and 2b have the biggest environmental effect in most impact categories. The production of cement and lime for drilling waste solidification was the main contributor to fossil depletion (64% of the total amount for scenario 2a and 54% for scenario 2b), and greenhouse gas emissions (49% of the total amount for scenario 2a and 70% for scenario 2b). However, the application of soil-like material (solidified drill cuttings) as an inert ground in swampy areas can make migration of heavy metals possible. Scenario 3 (reinjection) is associated with the least impact on the environment and the main contributor is electricity production (75% of greenhouse gas emissions). Sensitivity analysis shows that oilfield location does not affect the data for reinjection, but the impact assessment changes up to 60% for drill cutting disposal due to different waste pit design depending on permafrost

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and groundwater levels. Differences in the mass of used cement and lime change results for solidification scenarios considerably (up to 80%).

Keywords Drilling waste, Water-based drill cuttings, Drilling waste pit, Pitless drilling, Permafrost, Outlying territories, Material flow analysis, Assimilation, Climate change

1 Introduction

The process of oil and gas production, and well drilling in particular, is accompanied by waste generation. Drilling wastes are the second largest volume of waste, behind produced water, generated by the oil and gas exploration and production industry [1]. Drilling waste includes drill cuttings, used drill mud, and drilling wastewater. In the process of drilling a well, drilling fluid is supplied to lubricate and cool the tool, compensate for downhole pressure, reduce the intensity of cavern formation, strengthen the walls of the well, and bring the drilled rock to the surface [2]. Drill cuttings are formed after the exit of used drill mud with particles of the drilled rock at the surface resulting from its subsequent cleaning. At the end of drilling a well or its separate interval, and upon reaching the point of no further use, the used drilling fluid also becomes waste. When the drilling site, drilling equipment, and tools are flushed, drilling wastewater is generated [3].

Every year, the number of wells put into operation increases, therefore, the volume of drilling waste generated also grows, which is an urgent problem that requires constant monitoring and incurs large monetary costs [4, 5]. In fact, according to data from Rosneft [6], the largest oil and gas company in Russia, formed about 4 Mt of drilling cutting alone.

Drilling waste contains water, drilled rock particles, oil, and drilling mud components in various proportions. Different fields are characterized by unique composition of drilling waste and significant variation in the components to be found there [3]. The composition of drilling waste is influenced by the drilling technologies used, the location of the oil production facility, the geological and geochemical features of the rocks, the composition of chemical reagents used for the preparation and processing of drilling fluids, etc. [7].

Around the world, the treatment of drilling waste offshore and onshore differs significantly. Drilling waste discharging and reinjection are usually applied for offshore drilling, while landspraying, solidification, biological and thermal treatment, disposal are used for onshore drilling [3].

In this regard, the need often arises to choose the most appropriate drilling waste treatment technology.

The methodology of life cycle assessment (LCA) is widely used today for a variety of purposes, particularly, to justify decisions in the oil and gas industry, for example for environmental evaluation of oil and gas deposits, and also for assessing methods and technologies of oil extraction and processing [7, 8]. But there are very few examples of LCA application for comparative evaluation of drilling waste management technologies. LCA was used to evaluate options for wastewater management in the production and processing of oil [9], and to justify the choice of drilling fluids [10]. LCA was also applied to compare alternative options for drilling waste management in Algeria [11]. Four scenarios of treatment and disposal were compared: thermal desorption, stabilisation/solidification offshore, stabilisation/solidification onshore, and disposal without treatment. Disposal had the highest contribution to the human health, climate change and resources damage. The life cycle impacts of treatment of typical oil-based drill cuttings using low-temperature thermal desorption were explored with a case study in British Columbia, Canada [12]. The process contribution analysis found that thermal desorption process accounted for 80–95% of impacts in almost all impact categories. LCA was also applied to evaluate offshore drilling operations, including oil-based drill cuttings and fluids treatment in historical, current and future best practice [13].

But these examples considered cover only some types of drilling waste and technologies for handling them for rather specific local conditions. The management of water-based drilling waste onshore in the North has never been evaluated using LCA before, despite the fact that millions of tons of this type of waste are generated and treated annually.

The main research question of this study is which aspects of oil field characteristics, drilling waste properties and features of treatment technologies are of the greatest importance for the appropriate environmental assessment of waste management scenarios. Taking into account the diversity of oil and gas fields, the constantly changing legislation in the field of waste management and the development of new technologies for waste treatment, it is important not to create a list of "ideal" technologies for any cases, but rather to develop and to test an approach for comparative analysis of technologies encompassing all stages of the waste life cycle.

Based on the research questions, this study has a following research objectives: (1) to analyze the material flows and the life cycle of drilling waste for the most used treatment technologies; (2) to determine the influence of oil field peculiar properties and drilling waste composition on the LCA results; and (3) to identify the steps and processes of drilling waste management that have the greatest impact on the environment.

The study makes a novel contribution to the existing literature of drilling waste treatment technology comparison because of several reasons. First, there are no previous studies on LCA of drilling waste management in the conditions of the far north, permafrost and swamps. Second, this study was performed for water-based drilling waste, which in itself is a rarity, since oil-based drilling waste is most often analyzed. In addition, this study analyzes the possible impact of waste composition on the assessment results.

2 Materials and methods

The following data were initially used for LCA of drilling waste and comparative analysis of drilling waste management technologies: (1) geographical and climate characteristics of the oil field under consideration, its transport accessibility; (2) chemical composition and properties of drilling waste, conditions of their generation and accumulation, current treatment and disposal practices; and (3) characteristics of alternative methods of drilling waste management, including requirements for reagents and equipment.

2.1 Oilfield and drilling waste characteristics

Drilling waste generated at Novoportovskoye oil and gas condensate field (OGCF) located on the territory of Russia (67°53′04″ N latitude, 72°25′46″ E longitude), in the north of western Siberia, approximately 2200 km northeast of the city of Moscow with severe climate conditions and bad transport infrastructure was hypothetically selected as the object of research because more and more such oil deposits are exploited there.

Novoportovskoye OGCF is located on outlying territories of the Far North tundra and permafrost. Due to the location of this oilfield, there are long distances to travel for the delivery of reagents (190 km by truck and thousands of km by rail depending on the manufacturer's location) and all objects are built in mounds of artificial soil because of permafrost and high groundwater levels. Also, a lot of sand is necessary for waste pit construction.

2.2 Drilling waste properties

Drilling waste samples usually contain 0.8–7.5% oil and up to 15% organic compounds (petroleum products and chemical reagents) [14]. Drilling waste generated with oil-based drilling fluid is characterized by a higher petroleum product content in comparison to water-based drilling fluid and, accordingly, it has a more significant impact on the environment and demands a more responsible attitude [15].

To compare technologies, drilling waste obtained from drilling production wells using water-based solutions was considered, because it is commonly used in Russia. According to the average data on the composition of drilling cuttings (based on data from 21 oilfields of one of the largest Russian oil companies for the period of 2012–2017), it can be assumed that the waste mainly consists of drilled rock and water, and that it contains a number of environmentally toxic components (Table 1).

Drill cuttings with a high content of petroleum products or salts (mainly sulfates and chlorides) after special types of drilling fluids (oil-based, saltwater etc.) application, are not considered in this paper since they are rarely formed.

2.3 System boundaries and functional unit

The process of drilling and drill mud cleaning is not considered in this study, and 1 kt of drill cuttings (after pitless drilling) or the solid phase of drilling waste after sedimentation and removing the liquid phase (when drilling waste pits are applied) are used as the functional unit. At this stage of research, only the treatment of drill cuttings is taken into account, after preliminary sedimentation and removal of the liquid waste. It is accepted that liquid drilling waste in all scenarios is sent for reuse to the reservoir pressure maintenance system and is not considered further.

The boundaries of the system under consideration include all the stages of drill cuttings management from

Table 1 Drill cuttings composition

Element	Content (ppm, wet mass)		
	Average	Min	Max
Hydrocarbons	14,600	8400	60,000
Sulfates	5400	770	10,000
Chlorides	4100	100	18,500
Phosphates	340	40	500
Barium (Ba)	44,000	60	15,800
Iron (Fe)	28,000	4600	41,400
Manganese (Mn)	1000	60	1870
Cobalt (Co)	470	1.0	3150
Chromium (Cr)	100	60	240
Copper (Cu)	74	3	180
Zinc (Zn)	74	10	160
Nickel (Ni)	27	4	36
Lead (Pb)	14	2.3	30
Arsenic (As)	4.2	0.7	6.0

the accumulation of drilling waste in waste pits to the assimilation of drilling waste or products derived from drilling waste into the environment.

2.4 Waste treatment technologies and management scenarios

Common methods of drilling waste treatment in offshore drilling operations are discharged into a marine environment under specific conditions [16] and then reinjected into a subsurface formation [17, 18]. The main disadvantage of reinjection is the risk of ground water contamination.

Onshore landspraying (spraying waste onto topsoil), landspreading (spreading waste onto the shallow subsoil), and landfarming (spreading waste onto land and mixing it with topsoil to allow bioremediation of the hydrocarbons) are widely used in the USA and Canada [19]. Periodic treatment of the mixture of soil and drilling waste (to increase aeration), and the addition of nutrients and other additives (manure, straw, etc.) can enhance the aerobic biodegradation of hydrocarbons and prevent the development of conditions that promote leaching and mobilization of organic and inorganic pollutants from drilling waste. These methods are most effective in a mild climate [20]. Vermicomposting uses worms to remediate the drilling cuttings converting them in to a compost type material that can be used as a soil enhancer or fertilizer [21]. Bioaugmentation, biostimulation and phytoremediation of drilling waste reduce the content of heavy metal compounds and some volatile organic compounds [22]. Solidification is one of the most popular methods of drilling waste disposal, allowing users to reduce the solubility and mobility of pollutants [23–25]. Thermal disposal methods are commonly used for waste generated during drilling with oil-based drill fluids [12, 26]. Currently, drilling waste is also used for the production of building materials. A mixture of drilling waste and various binders (Portland cement, lime, sand, loam, etc.) allows consumers to obtain materials that can be used for recultivation, and strengthening of roadside slopes, embankments, and quarries, as well as landfill dredging and reclamation [27].

In Russia, the most common method of onshore drilling waste treatment is disposal into drilling waste pits. The advantage of this method is the option for waste disposal on each multi-well pad with a capacity corresponding to the volume of drilling waste generated. However, it takes up significant land areas and poses a potential danger to the environment because of possible emissions and leaching. Drilling waste disposal in pits leads to significant environmental pollution and cannot be considered as a promising technology for drilling waste treatment. It has therefore been replaced by other technologies in numerous oil and gas companies. Currently, many technologies in the field of drilling waste management are offered in the Russian market of services and equipment. For example, several dozen technologies developed by different companies implement a common technological principle of solidification and differ in the reagents and formulations used, along with equipment and work performed.

To analyze and compare drill cuttings treatment technologies, it is necessary to understand where the technology is in the life cycle of drilling waste and what conditions are associated with it. Furthermore, it is essential to determine whether additional steps of waste treatment will be necessary and to know where and how the resulting product will be used.

In this paper, several scenarios of drilling waste management are considered: scenario 0 – landspraying; scenario 1 – disposal in waste pits; scenario 2 – solidification to obtain a soil-like material in two sub-scenarios with 2a) solidification in waste pits with abandonment of resulting material in waste pit and pit reclamation, and 2b) solidification on a special object (site or special equipment) using the obtained material as inert soil; and scenario 3 – reinjection into suitable deep geological formations.

Scenarios 0, 1, 2a include drilling with exploitation of waste pits, while scenarios 2b and 3 include pitless drilling. In order to simplify the research, liquid drilling waste in all scenarios is removed from the boundaries of the system, and its contribution to the negative impact on the environment is not taken into account, since it is accepted in all scenarios that liquid drilling waste is used in the reservoir pressure maintenance system, i.e. it is pumped into underground horizons.

For all considered scenarios, the quantitative values of all main flows were calculated, and a material flow analysis was constructed. The calculations take only single-use objects such as drilling waste pits into account. All objects that can be used repeatedly are not included, for example, tanks for the accumulation of drilling waste during pitless drilling or centralized solidification/ reinjection facilities.

Scenario 0 (baseline) includes surface spreading of drilling waste without any pretreatment. So, a minimum of technological operations for the distribution of solid drilling waste over the territory is assumed. In accordance with legislation of the Russian Federation, landspraying of drilling waste management is not allowed, but it is quite actively used in many foreign countries. According to the requirements of Canadian legislation [28, 29], it is possible to distribute drilling waste on the territory if a number of requirements for the quality of waste are met (the content of chlorides, hydrocarbons and other substances). This scenario was added as a baseline to assess the environmental impact of drilling waste itself and the impact of operations for drilling waste accumulation, transportation, processing, disposal, or assimilation of solidified waste. The environmental impact of drilling waste landspaying is the temporary occupation of land (while the assimilation of drilling waste is underway, it will not be possible to use it for other purposes), assimilation of pollutants contained in drilling waste, drilling waste transportation and truck spreader operation.

For scenario 1, five main stages were identified (Fig. 1), starting with the construction of a drilling waste pit and ending with its reclamation. Drilling waste pit construction involves the use of a geomembrane (a high-density polyethylene layer with a thickness of 1.5 mm or more) to prevent migration of pollutants contained in the drilling waste into soils and water bodies. However, this only occurs if we consider the short-term environmental impacts of drilling waste disposal. When assessing long-term impacts, it is necessary to bear in mind that the

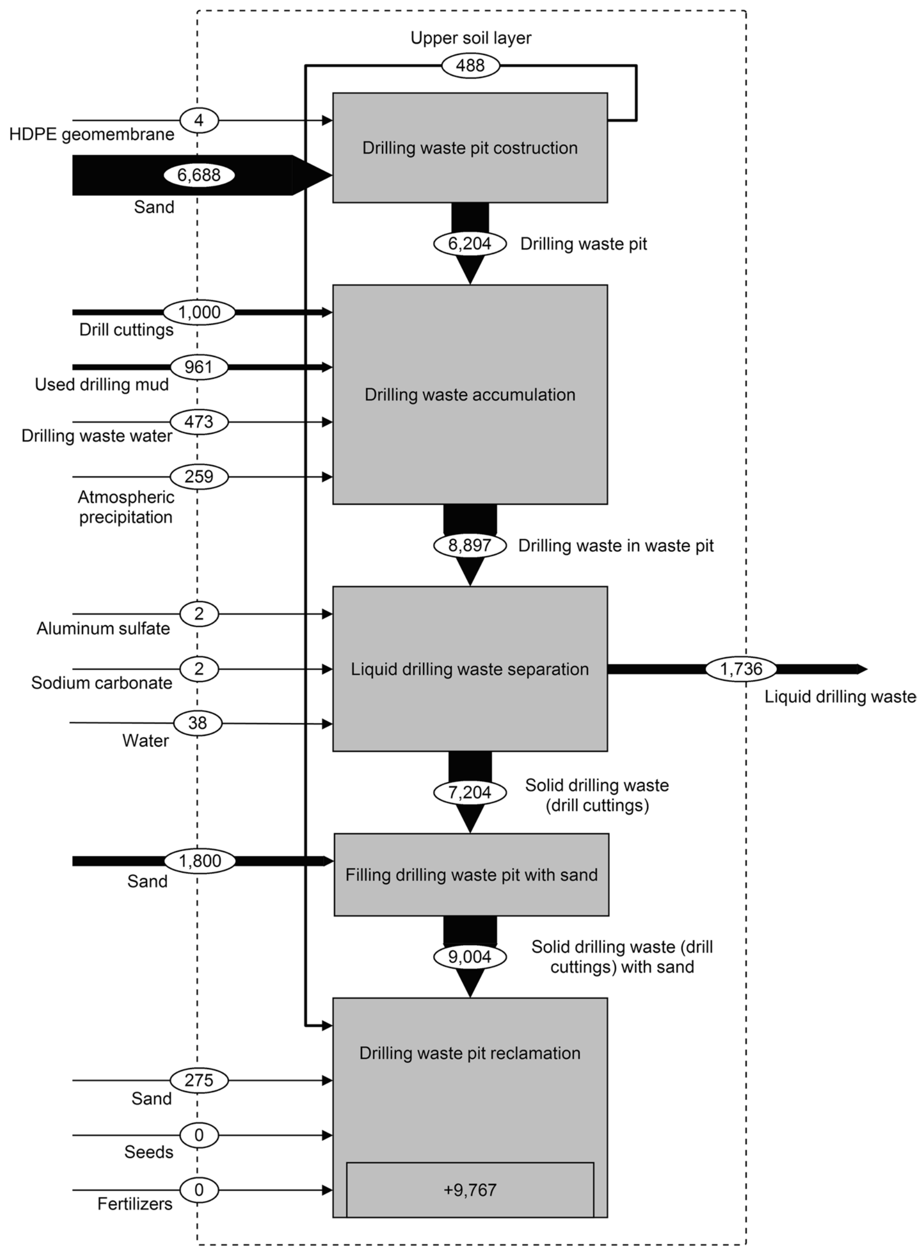

Fig. 1 Material flows of Scenario 1. Drill cuttings disposal in waste pits

geomembrane will collapse, and pollutants will enter the environment.

For scenario 2a, five main stages were also identified, starting with the construction of a temporary sludge storage facility and ending with its reclamation. The first three stages and the last one are similar to scenario 1 (Fig. 1), but instead of filling the waste pit with sand, some reagents are added for waste solidification. Solidification technologies are very diverse in terms of the reagents used, recipes, and process conditions. In this regard, the option of solidification with cement and lime is considered to be most frequently used. This emphasis on the use of cement and lime is primarily related to the specifics of these materials – their production consumes a large amount of resources (in particular fossil fuels) and generates a significant amount of carbon dioxide emissions, which are taken into account in the LCA.

Drilling waste solidification using cement and lime assumes a range in how the reagents are proportioned, so the average values are used for calculations. The main quantitative characteristics of resource consumption are presented (Fig. 2).

Scenario 2b is the solidification of drill cuttings after pitless drilling. The main stage with the greatest impact on the environment is the solidification of drilling waste (Fig. 3). In this case, solidification takes place at a centralized waste management facility (using an excavator and a bulldozer as in the case of solidification in a waste pit, but on a special site with an impermeable surface). The resulting soil-like material is used in the construction of new multi-well pads. Transportation of drill cuttings and soil-like material is an integral part of the process.

Reinjection includes collecting cuttings from drilling wells, then mixing the cuttings with liquid waste, water and additives to create slurry, and finally injecting the slurry into a selected underground formation through an injection well. Material flow analysis for Scenario 3 is presented in Fig. 4. The effort put into the construction and maintenance of the reinjection site itself is not taken into account at this stage of the assessment.

For each scenario, the main quantitative characteristics of resource consumption were calculated, based on the data of a Russian oil production company (Table 2).

2.5 Emissions and metal leaching

In different scenarios, the end of the drilling waste life cycle is associated with different environmental impacts. With landspraying, there are no measures to isolate toxic components from the environment, moreover, this method is basically aimed at the most complete and rapid assimilation of waste. Therefore, it is assumed that all components of the waste completely enter the soil. All other scenarios provide isolation of hazardous waste components from the surrounding environment. In this regard, it is assumed that there is no emission of pollutants that can come into contact with humans or living organisms.

2.6 LCA method

A LCA was made in order to determine the environmental impacts of every scenario. The OpenLCA software version 1.10.3 from GreenDelta, Ecoinvent 3.8 database and ReCiPe Midpoint (H) impact assessment method were used for an environmental impact assessment.

3 Results and discussion

3.1 General results

The environmental impact of drilling waste management scenarios (per 1 kt of drill cuttings) is presented in Table 3.

Three environmental impact assessment categories were chosen for further consideration: «Fossil depletion», «Climate change» and «Human toxicity». For these categories, the main aspects of environmental impact are considered.

3.2 Fossil depletion, climate change and human toxicity

Figure 5 shows the results of a LCA of drilling waste by fossil depletion.

Fossil depletion is mainly associated with material and reagents consumption (sand for construction and reclamation of drilling waste pits, cement and lime for drilling waste solidification). Fossil depletion due to material and reagents consumption for scenario 1 is more than 59%, for scenario 2a is more than 64%, for scenario 2b is more than 54%. Production of electricity for drill cuttings grinding, slurry preparation, and pumping in scenario 3 is the reason of 75% of fossil depletion in scenario 3 due to the fact that natural gas is the main fuel for electricity production in Russia.

Figure 6 shows the results of the LCA of drilling waste management as determined by the level of greenhouse gas emissions («Climate change» impact category).

Greenhouse gas emissions of scenarios 2 depend mainly on the use of cement and lime (49% of the total amount for scenario 2a and 70% for scenario 2b), the production of which is associated with emissions due to the burning of fossil fuels and the decarbonization of raw materials. Thus, drilling waste solidification technologies involving the use of cement and lime are immediately significantly inferior to other options in terms of reducing greenhouse gas emissions.

Despite the obvious link between the use of fossil fuels and greenhouse gas emissions, the ratio of impact for different scenarios, especially for scenario 1 and 2b has changed, due to the use of different types of primary

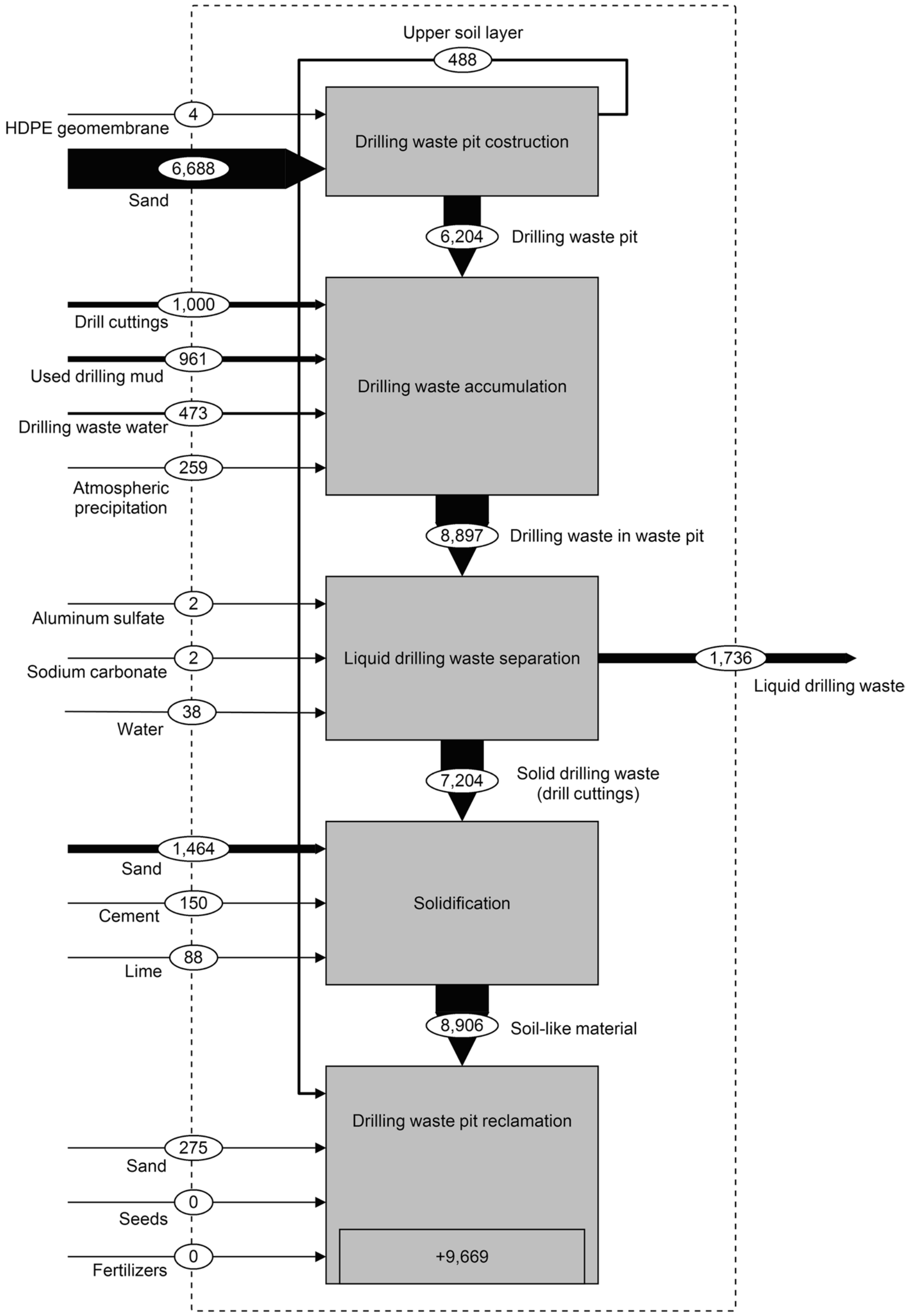

Fig. 2 Material flows of Scenario 2a. Drill cuttings solidification in waste pits

resources as energy sources for different processes. In addition, the decarbonization of raw materials in cement production leads to greenhouse gas emissions that are not caused by fuel combustion.

Figure 7 show the results of the life cycle assessment of drilling waste in the category «Human toxicity».

In terms of toxicity to humans, the main contributing factor is materials and reagents. But only if the migration of pollutants contained in waste, primarily heavy metals, into the soil are not considered. It is logical to assume that landspraying should be the worst option, if all other scenarios provide complete prevention of pollutants migration to the environment. But, in truth, it is more complicated, so pollutant migration in different scenarios is considered in more detail below.

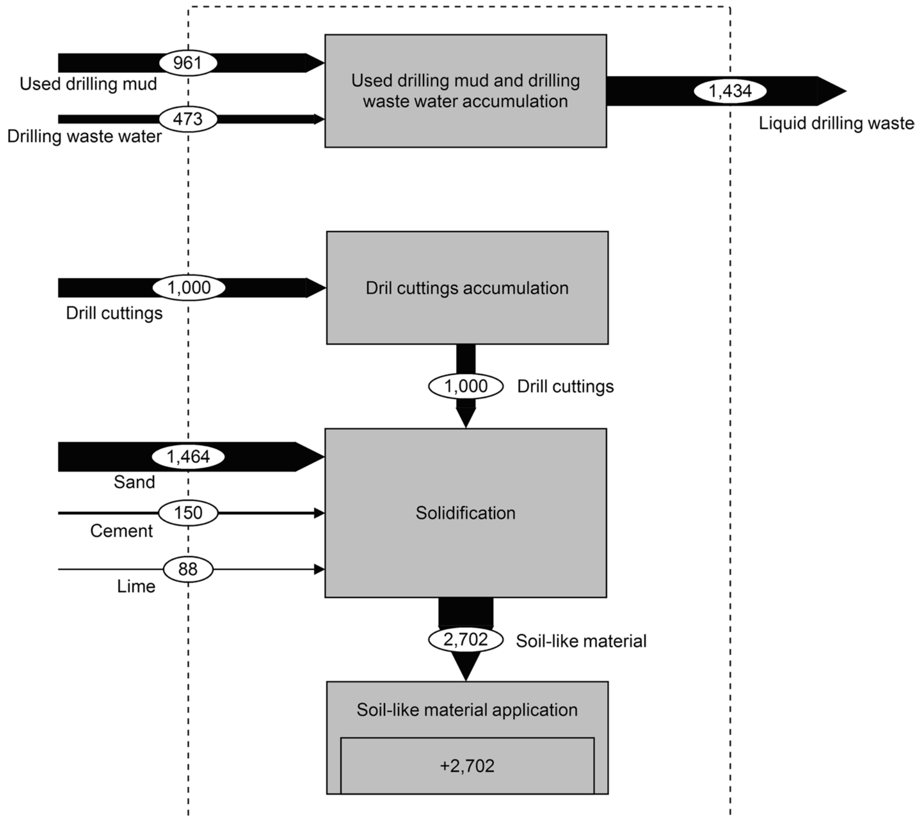

Fig. 3 Material flows of Scenario 2b. Drill cuttings solidification (pitless drilling)

3.3 Pollutant migration in different scenarios

Environmental impact of drilling waste assimilation was calculated separately. It takes place in three variations of drill cutting composition, according to Table 1. Migration of 100% toxic substances from waste to the soil was calculated. Results are presented in Table 4 (the mass of toxic substances is recalculated to 1,4 dichlorobenzene (DCB) equivalent in accordance with ReCiPe life cycle impact assessment method).

Assuming that only landspraying is accompanied by toxic substances migration from drill cutting into the soil the results of the toxicity assessment for humans will look like this (Fig. 8).

However, when assessing the environmental effect of drilling waste assimilation, it is necessary to take into account not only the waste composition, but also the characteristics of the territory and its ability to assimilate. In particular, in the forest-tundra zone of Western Siberia (Russia) cryogenic conditions and the seasonal thawing of permafrost could change the downward flow of matter [30].

All operations that isolate drill cuttings from the environment will have less negative environmental impact in comparison to landspraying if drilling waste with average concentrations of heavy metals is treated. At the same time, significant variability in the composition of drill cuttings leads to the fact that landspraying will have less impact on the environment than solidification with cement only if waste with minimal pollutant content is considered. So, waste composition analysis is extremely important for choosing a drill cuttings treatment option.

In fact, scenarios 1–3 are also associated with certain risks of pollutant migration.

If everything is done correctly for reinjection and suitable underground horizon was found, this method provides complete isolation of waste from underground water and ensures the prevention of pollutant migration [31, 32].

High-density polyethylene (HDPE) geomembrane is commonly used as a bottom liner in waste pit construction. It prevents migration of pollutants into the environment. But HDPE geomembrane degrades with time by oxidation, radiation, extreme temperatures, or chemicals. It is estimated that the service life of an HDPE geomembrane is 45–500 years depending on the surrounding operating conditions [33]. When HDPE geomembrane is used for drilling waste pit construction, it can be assumed that there will be no cracks of the geomembrane in the initial period of more than 100 years, because

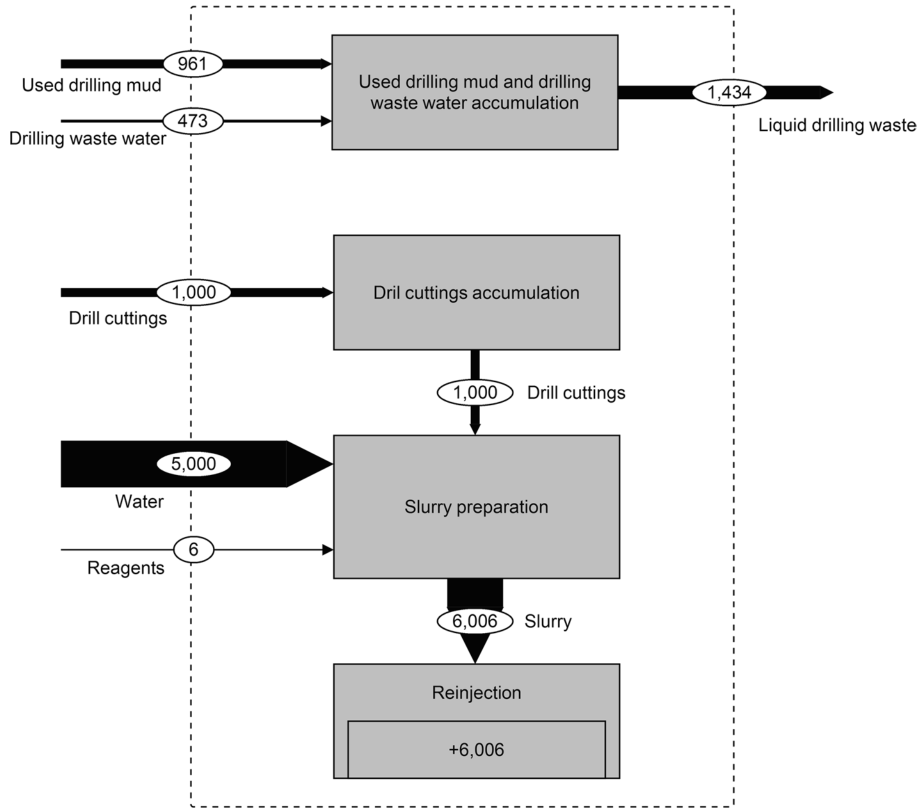

Fig. 4 Material flows of Scenario 3. Drill cuttings reinjection

drilling waste is not as chemically active as the solutions that are usually used to determine the resistance of the membrane in laboratory tests.

Solidification/stabilization of waste with cement as a binder is applied for heavy metals immobilization by converting them into a less soluble form and encapsulating them by creating a durable matrix. In this case, properties of treated waste are the main barrier for prevention of environmental pollution. The pH of drilling waste depends on the territory, the depth of drilling and a number of other factors, but usually drilling waste has an alkaline reaction and a pH of about 8.5–10.5 (in some cases up to 12.7) [25, 34, 35]. Soil-like materials obtained during drilling waste solidification with cements are usually even more alkaline (pH 12.0–13.5). In this regard, soil-like materials are usually stable enough when exposed to water, atmospheric precipitation, carbon dioxide in the surrounding air, or acid rain conditions [25, 36–39]. Metals migration in these cases is minimal and sometimes even lower than the detection limit of the instruments. However, simulation tests revealed that Co, Ni, Cu, Pb and Zn were of long-term release concern in acetogenic landfill conditions [39]. Leaching of all metals except Ba and Sr from solidified products was strongly affected by leachate pH [25]. So soil-like materials' exposure to an acidic environment can lead to the leaching of metals. The soil in the area of Novoportovskoye OGCF is swampy and its pH is 2.7–6.4 [40]. Consequently, the use of a soil-like material as an inert ground on the territory of swampy areas without any isolation may be accompanied by the migration of heavy metals into the environment. It can reasonably be assumed, that metals from soil-like material obtained by drilling waste solidification will most likely get into the environment over time.

The principle of multi-barrier protection is realized in scenario 2b. Toxic substance migration is prevented by the design of the waste pit (HDPE geomembrane) and by the quality of the materials (heavy metals immobilization with cement). So, emissions of pollutants are unlikely for very long period of time.

In this regard, it is assumed that in scenarios 2a and 3 there are no emissions of pollutants into environments that can come into contact with humans or living organisms. As for scenario 2b in a longer-term perspective, perhaps the pollutants will get washed out from soil-like material in an acidic medium, and become more and more similar to landspraying in terms of environmental impact.

Table 2 Life cycle inventory for treatment of 1000 tons of drill cuttings

Impact contributor	Scenario 0. Drill cuttings land-spreading	Scenario 1. Drill cuttings disposal in waste pits	Scenario 2a. Drill cuttings solidification (in waste pits)	Scenario 2b. Drill cuttings solidification (pitless drilling)	Scenario 3. Drill cuttings reinjection
Material consumption, t					
HDPE membrane		3.8	3.8		
Sand		8744.2	8427	1464	
Aluminum sulfate		2.1	2.1		
Sodium carbonate		2.1	2.1		
Fertilizer		0.04	0.04		
Seeds		0.02	0.02		
Cement			150	150	
Lime			88	88	
Reagents (thickeners, inhibitors, viscosifiers)					5.6
Water		38.2	38.2		5000
Transportation, km					
Drill cuttings	truck 50			truck 50	truck 50
Sand		truck 20	truck 20	truck 20	
PE geomembrane		truck 190, rail 3000	truck 190, rail 3000		
Aluminum sulfate		truck 190, rail 3000	truck 190, rail 3000		
Sodium carbonate		truck 190, rail 3000	truck 190, rail 3000		
Fertilizer		truck 190, rail 3000	truck 190, rail 3000		
Seeds		truck 190, rail 3000	truck 190, rail 3000		
Cement			truck 190, rail 1000	truck 190, rail 1000	
Lime			truck 190, rail 1000	truck 190, rail 1000	
Soil-like material				truck 50	
Reagents					truck 190, rail 3000
Diesel consumption for equipment operation, kg					
Truck spreader	3200				
Excavator		5140	6620	1950	
Bulldozer		5540	5540	1050	
Cementing truck		430	430		
Electricity consumption for equipment operation, kWh					
Grinders and pumps					60,000
Land occupation, m^2*year					
Land occupation	250,000*1 (wetland)	2540*2 (wetland)	2540*2 (wetland)		

3.4 Sensitivity analysis

The sensitivity analysis was based on different oilfield locations. The same scenarios of drilling waste management were considered for Orenburg OGCF, which is a significantly different oilfield, in order to assess the impact of local conditions on the choice to become more involved with drilling waste treatment technology.

The principal differences between Novoportovskoye and Orenburg OGCF are:

1. Different distances for the delivery of reagents. Orenburg OGCF is located in the south of Russia just 30 km from Orenburg. It has a large, convenient railway station and a good road network, so less transportation of reagents is required.
2. Different designs of drilling waste pits – in the conditions of the Orenburg OGCF, less sand is necessary for waste pit construction because of the low ground water level and the lack of necessity for embankment. Also, there is less excavator and bulldozer work, and transportation of sand is required.
3. Different types of land. Novoportovsky OGCF is located on wetlands, while Orenburg OGCF is on grassland.

Table 3 Environmental impact of drilling waste management scenarios (per 1000 tons of drill cuttings)

Impact category	Reference unit	Scenario 0. Drill cuttings land-spreading	Scenario 1. Drill cuttings disposal in waste pits	Scenario 2a. Drill cuttings solidification (in waste pits)	Scenario 2b. Drill cuttings solidification (pitless drilling)	Scenario 3. Drill cuttings reinjection
Agricultural land occupation - ALOP	m^2 a	2.53E+05	7.63E+03	9.71E+03	2.60E+03	428
Climate change - GWP100	kg CO_2-eq	2.44E+04	1.82E+05	4.02E+05	2.79E+05	6.05E+04
Fossil depletion – FDP	kg oil-eq	8.33E+03	6.32E+04	9.41E+04	5.25E+04	2.10E+04
Freshwater ecotoxicity – FAETPinf	kg 1,4-DCB-eq	473	2.34E+03	3.64E+03	1.85E+03	1.92E+03
Freshwater eutrophication – FEP	kg P-eq	3.1	23.6	47.6	29.7	29.0
Human toxicity – HTPinf	kg 1,4-DCB-eq	6.80E+03	4.25E+04	7.26E+04	4.56E+04	2.36E+04
Ionising radiation - IRP_HE	kg U^{235}-eq	1.54E+03	1.35E+04	1.94E+04	1.02E+04	1.46E+04
Marine ecotoxicity – METPinf	kg 1,4-DCB-eq	451	2.32E+03	3.54E+03	1.84E+03	1.73E+03
Marine eutrophication – MEP	kg N-Eq	74	547	784	404	66
Metal depletion – MDP	kg Fe-eq	2.04E+03	1.14E+04	1.68E+04	8.32E+03	1.97E+03
Natural land transformation - NLTP	m^2	7.9	299.5	319.9	81.8	8.2
Ozone depletion – ODPinf	kg CFC-11-eq	0.0036	0.0274	0.0364	0.0189	0.0077
Particulate matter formation - PMFP	kg PM_{10}-eq	81	579	849	440	163
Photochemical oxidant formation - POFP	kg NMVOC	223	1.66E+03	2.35E+03	1.20E+03	194
Terrestrial acidification - TAP100	kg SO_2-eq	148	1.15E+03	1.71E+03	898	241
Terrestrial ecotoxicity – TETPinf	kg 1,4-DCB-eq[a]	6.5	42.9	54.3	33.4	5.9
Urban land occupation – ULOP	m^2a	1.14E+03	4.79E+04	5.44E+04	1.61E+04	703
Water depletion – WDP	m^3	29	2.14E+04	2.17E+04	3.87E+03	1.13E+04

[a] *1,4-DCB* 1,4-dichlorobenzene

Figure 9 shows the deviations in the values for the selected categories when changing oilfields.

Despite the fact that very different oilfields were selected for comparison, the influence of this factor on the final results was negligible for a reinjection scenario because only the delivery distance for a small number of reagents changed. On the other hand, the oilfield location had a far more significant influence on the scenarios using a waste pit, due to big differences in its design that affected the required quantity of sand and operating time of the equipment at each site.

Also, as it was already said, different solidification technologies assume different mass of cement and lime per 1 t of drill cutting. Previously average value was taken for calculation – 150 kg of cement and 88 kg of lime per 1 t of drill cuttings. In fact, the mass of cement could be from 100 up to 300 kg and the mass of lime from 0 (not used) up to 200 kg. So, this range of values was taken for sensitivity analysis.

Results of sensitivity analysis are presented in Figs. 10, 11 and 12.

Thus, cement and lime application significantly affects the assessment results of waste solidification scenarios.

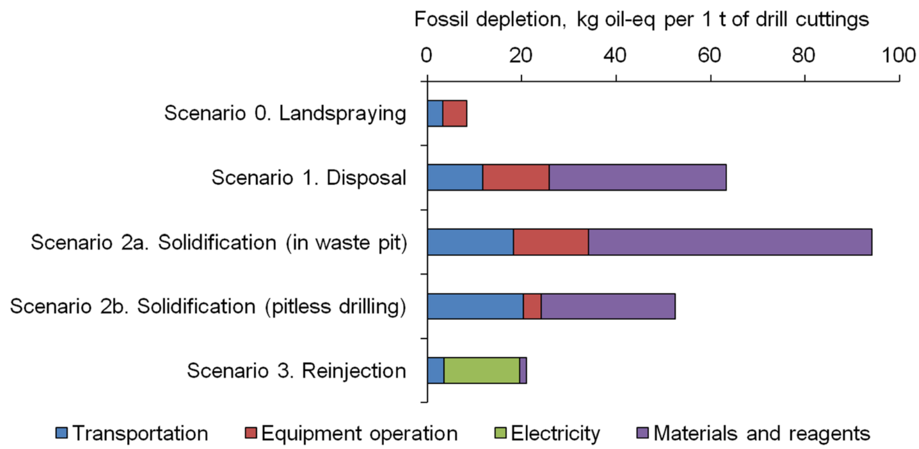

Fig. 5 Fossil depletion for drilling waste management scenarios by contributors

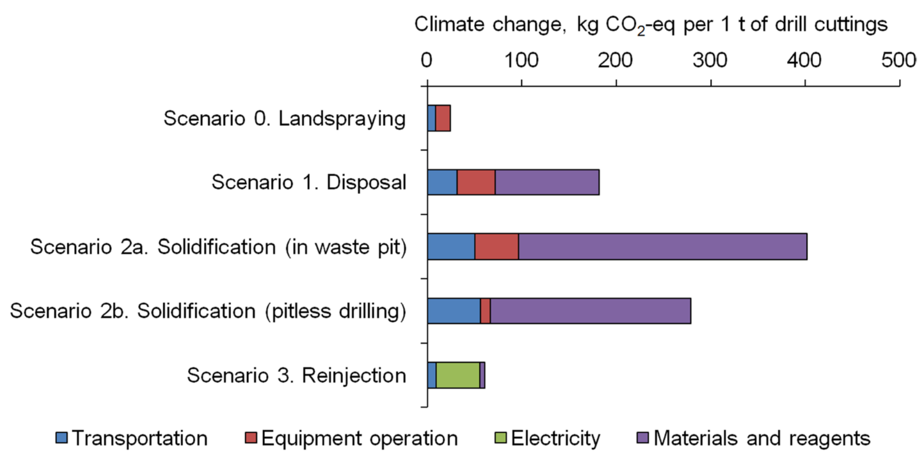

Fig. 6 Climate change for drilling waste management scenarios by contributors

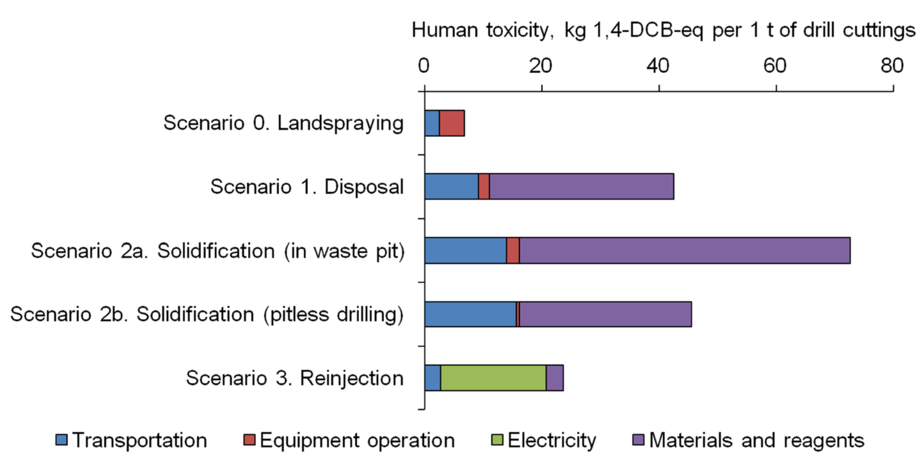

Fig. 7 Human toxicity for drilling waste management scenarios by contributors

Table 4 Environmental impact of drilling waste assimilation (per 1 kt of drill cuttings)

Impact category	Reference unit	Assimilation (average)	Assimilation (minimum)	Assimilation (maximum)
Freshwater ecotoxicity - FAETPinf	kg 1,4-DCB-eq	3,99E+04	90	5,27E+04
Human toxicity - HTPinf	kg 1,4-DCB-eq	7,32E+05	1,04E+04	2,64E+06
Marine ecotoxicity - METPinf	kg 1,4-DCB-eq	2,52E+04	54	3,31E+04
Terrestrial ecotoxicity - TETPinf	kg 1,4-DCB-eq	4,03E+04	211	6,94E+04

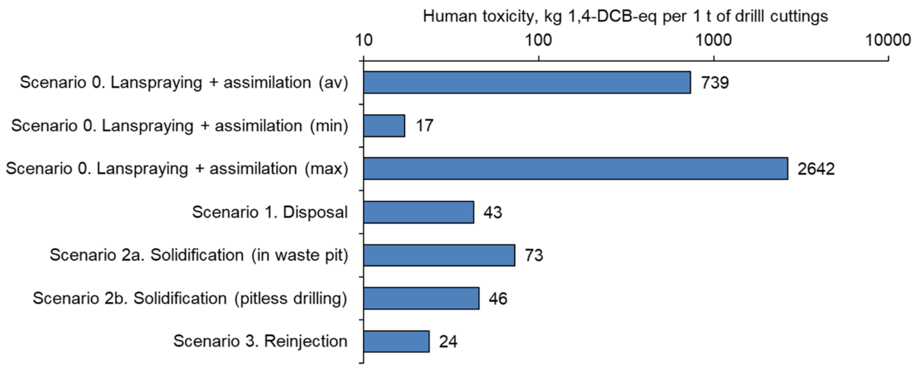

Fig. 8 Human toxicity for different scenarios with assimilation for landspraying scenario

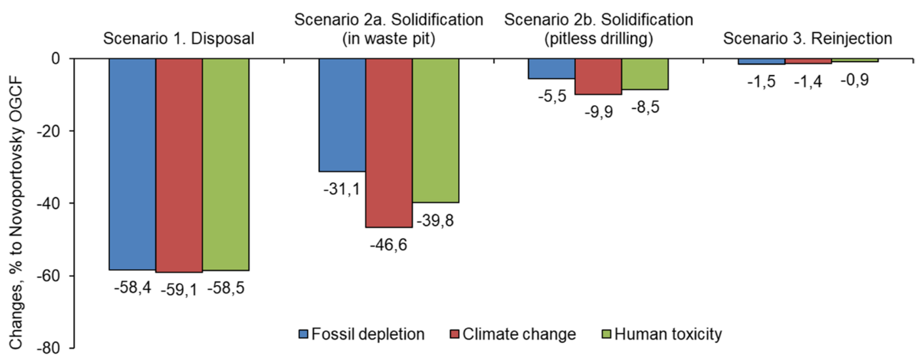

Fig. 9 Differences in impact categories for Orenburg OGCF in comparison with Novoportovsky OGCF

And yet, even taking into account such significant differences in categories for Orenburg OGCF, the final ranking of scenarios remains the same.

As for the migration of pollutants into the environment from waste, it is necessary to consider the following differences between the two oilfields. As already mentioned, Novoportovsky OGCF is located on wetlands (soil pH 3–6) and Orenburg OGCF on farmland (soil pH 6–7). As a result, there are different conditions for heavy metal leaching. At Orenburg OGCF, the application of soil-like material outside of the waste pit should lead to significantly less metal leaching. That being said, there is no data at the moment on the basis of which it would be possible to predict the migration of pollutants into the soil, based on the properties of waste, type and quality of reagents used, and soil properties. For all scenarios, waste or soil-like material assimilation is not included to compare the impact from waste assimilation itself and waste treatment operations. Among all given options, landspraying is associated with the lowest environmental impact at the waste treatment stage, since it requires minimal efforts.

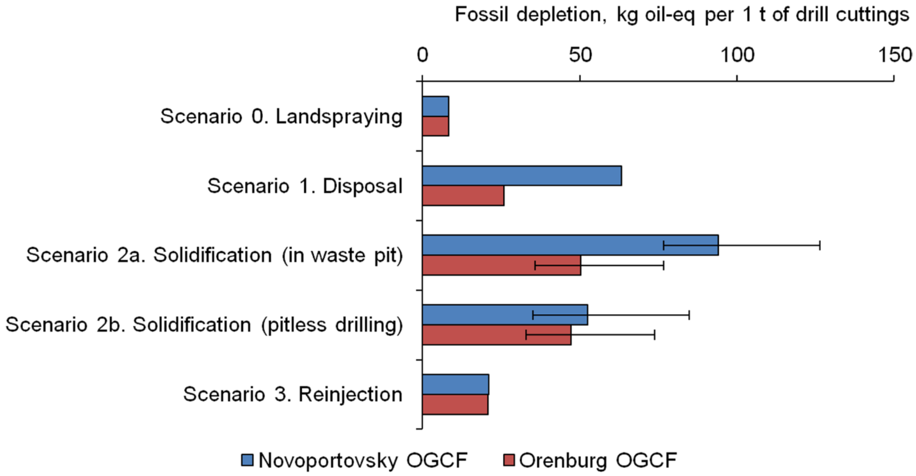

Fig. 10 Fossil depletion for drilling waste management scenarios for Novoportovsky OGCF and Orenburg OGCF

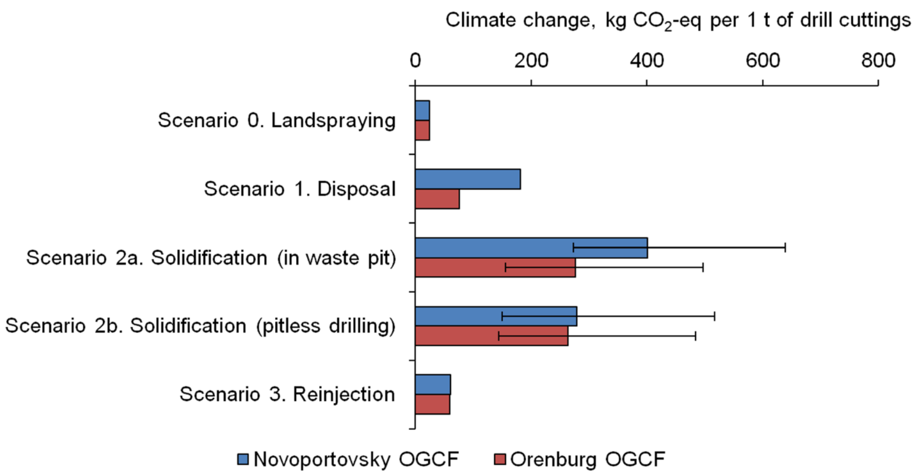

Fig. 11 Climate change for drilling waste management scenarios for Novoportovsky OGCF and Orenburg OGCF

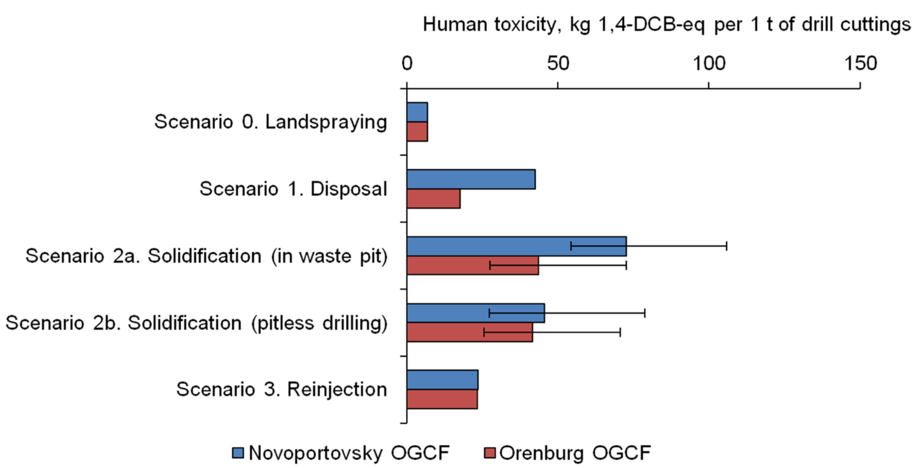

Fig. 12 Human toxicity for drilling waste management scenarios for Novoportovsky OGCF and Orenburg OGCF

4 Conclusions

Currently available methods and approaches to substantiate the technology for drilling waste management in the Russian Federation are either primarily aimed at technical and economic assessment, or are often based on methods of expert assessment. Quantitative assessment of the environmental effectiveness of waste management systems is practically unheard-of. Therefore, it is clear that LCA is a promising methodology for comparison of drilling waste treatment options.

LCA was made for drilling waste management technologies that are widely-used in Russia, such as disposal in waste pits and solidification along with landspraying (widely used in Canada, but not yet allowed in Russia), and reinjection, which is known to have good prospects for implementation. The impacts are shown in the categories of «Fossil depletion», «Climate change» and «Human toxicity».

The following significant findings were made as a consequence of this study:

- The environmental impact of landspraying itself is relatively small in all impact categories (at least two and a half times less in comparison with reinjection and six times in comparison with solidification), but migration of heavy metals in the soil has significant negative consequences. So, landspraying can be used only for waste with minimum levels of pollutants.
- Cutting reinjection delivers the lowest environmental impact in most categories and in general among all scenarios and promises the least risks to the environment. For comparison, greenhouse gas emissions equal to 60 kg of carbon dioxide per 1 t of drill cuttings during reinjection and to 279–402 kg when solidification was applied.
- Scenario 2a (solidification in waste pit) has the highest level of impact not only in the impact category of climate change, but also in fossil depletion (94 kg oil-eq per 1 t of drill cuttings) and human toxicity (73 kg 1,4-DCB-eq per 1 t of drill cuttings). According to the results, environmental impact for scenarios 2a and 2b is mostly associated with material consumption, primarily cement and lime. Changing the dosage of cement and lime for scenarios 2a and 2b within the intervals that are applied in practice leads to significant changes. Greenhouse gas emissions change from minus 32 to plus 59% in comparison with the basic calculations.
- Scenario 1 is the most sensitive to changes in the location of the oilfield due to waste pit design peculiarities. Greenhouse gas emissions are up to 60% low if there is no need for embankment, that is used for pit the regions with permafrost and swamps.
- Oil field location has a significant impact on the final assessment of waste management scenarios. At the same time, transport accessibility plays a small role in comparison with climatic conditions and the type of ecosystem, on which the destructive features of the technologies used and the amount of resources spent will depend.
- Drilling waste composition is fundamentally important to justify the choice of treatment technology, especially if the technology involves the assimilation of waste in the environment. Attention should be paid not only to the oil content in the waste, but also to the concentrations of heavy metals.

Main limitation of the study is uncertainty about the possibility of pollutant leaching from solidified waste and the dynamics of such leaching over time and depending on initial waste composition, leaching conditions and the reagents used. In addition, the presented results were obtained only for the treatment of water-based drilling waste in Russia.

Findings and limitations allow formulating some recommendations and directions for further research.

- The stability of materials obtained as a result of drilling waste solidification and membranes at the bottom of waste pit, especially in the acidic environment of swamps and at low temperatures, requires additional research.
- The stability and longevity of waste pit construction and HDPE membranes are also introduce great uncertainty into the results of the study. In general, the concept of multi-barrier protection in relation to drilling waste requires additional research. It is necessary to determine how appropriate is it to spend resources and get emissions when simultaneously solidifying waste and installing an impermeable layer at the bottom of waste pit.

The results of this study contribute to a developing understanding of the environmental impacts from the waste management actions themselves in an attempt to reduce waste negative impact on air, water, soils and human health. The results clearly showed that sometimes it is better for environment just to spread waste with a low content of hazardous substances over the territory instead of curing them with cement and lime. It is also a good reason to think about the expediency of waste solidification despite the waste composition, which is now mandatory according to the legislation of Russia.

The major practical contribution of the present research is that it provides additional data for decision makers. The results of this work can be used by oil and gas companies in the development of waste management strategies, concepts and plans, as they enhance their ability to choose drilling waste management technologies while also continuing to apply the current criteria for technical and economic assessment.

Acknowledgements
The authors wish to thank the staff of the Laboratory of environmental management and nature-inspired technologies of the Perm National Research Polytechnic University for their cooperation during source data collection.

Authors' contributions
Conceptualization, G.I. and J.F.; methodology, G.I., N.S. and J.F.; investigation, G.I. and J.F.; data curation, V.K. and N.S.; writing—original draft preparation, I.S., J.F., and V.K; writing—review and editing, N.S., G.I., V.K. and J.F.; visualization, N.S and G.I; supervision, N.S. and V.K.; project administration, G.I.; funding acquisition, N.S. All authors read and approved the final manuscript.

Funding
The study was performed with financial support from Ministry of science and higher education of the Russian Federation (Project № FSNM-2020-0024 «Development of scientific basis for environmentally friendly and nature-inspired technologies and environmental management in petroleum industry»).

Availability of data and materials
All data generated or analysed during this study are included in this published article.

Declarations

Competing interests
The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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Received: 6 August 2022 Accepted: 23 February 2023
Published online: 16 March 2023

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