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Title: Effects of hydrocarbon extraction on freshwaters

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Structured abstract

Aim: This chapter explains hydrocarbon extraction and discusses its effects on inland water resources.

Main concepts covered: Section 1 provides an overview of the history of hydrocarbon extraction, the occurrence, and formation of hydrocarbon resources, and explains the conventional and unconventional hydrocarbon extraction techniques. Section 2 discusses the main impacts associated with conventional and unconventional oil and gas extraction on freshwaters. This discussion covers distinct water resource impacts associated with hydrocarbon extraction, acute, ecological, and legacy impacts on surface water and groundwater resources, and water-related socio-economic impacts. Section 3 covers management tools to minimize negative impacts. Throughout, case studies that mostly stem from Africa and South America are used to illustrate impacts and related management options. A detailed glossary explains technical concepts.

Conclusion: The discussion of impacts clearly illustrates that oil and gas extraction imperils water resources next to fuelling climate change. Considering the Paris agreement of limiting global temperature increases to 1.5 °C, governments should therefore limit fossil fuel extraction and pursue sustainable development to ensure a liveable planet for current and future generations.

Keywords: Hydrocarbon extraction; conventional oil and gas; unconventional oil and gas; water resource impacts; management tools; future of oil and gas extraction.

Glossary of main terms

Conventional oil and gas:	Conventional oil and gas resources are produced from conventional reservoirs. Conventional oil is trapped underneath seals in deep porous geological formations. Gas that occurs in association with this oil, is called associated gas. This oil and gas migrated from unconventional reservoirs like shale. Gas that occurs in a porous formation underneath a seal and that is not associated with oil, is called non-associated gas.
Conventional reservoir:	For oil gas reserves, conventional hydrocarbons refer to hydrocarbons that are produced from reservoirs that do not require stimulation to produce the gas. These reservoirs typically have permeabilities larger than 1 milliDarcy. The oil in these reservoirs migrated from source rocks and accumulated in the reservoirs (commonly porous sandstone or carbonate). Conventional reservoirs are capped by impenetrable material (often shale or salt) that keeps the conventional oil in place.
Groundwater:	Water that occurs below the surface of the earth, where it occupies all or part of the void spaces in soils or geologic strata.
Hydraulic fracturing:	The act of pumping hydraulic fracturing fluid into a formation to increase its permeability. Hydraulic fracturing has been used in the industry in various forms, for either stimulation of water wells to produce water, or for stimulation of oil and gas wells to produce oil and/or gas. Various technologies can be combined or used separately during hydraulic fracturing. It may involve the use of only water (for water well stimulation) or a combination of any or all of four separate technologies, viz. directional drilling, the use of high volumes of fracturing fluids, the use of slickwater additives, and the use of multi-well drilling pads. When all four technologies are combined it is more specifically called ‘High-volume slickwater long-lateral’ (HVSLL) stimulation. Hydraulic fracturing as used in the oil and gas industry commonly includes the usage of 0.5-2% chemical additives (slickwater additives), large volumes of proppant as well as large volumes of fluid. Base fluids that may be used may include water, liquid petroleum gas, or other gases such as nitrogen or carbon dioxide. Synonyms for hydraulic fracturing as used in the oil and gas industry include ‘slickwater fracking’ (slickwater in short), ’high volume hydraulic fracturing‘, or just ’fracking‘ or in short.
Hydrocarbon:	A naturally occurring organic compound comprising hydrogen and carbon. Hydrocarbons can be as simple as methane [CH_4], but many are highly complex molecules and can occur as gases, liquids, or solids. The molecules can have the shape of chains, branching chains, rings, or other structures. Petroleum is a complex mixture of hydrocarbons. The most common hydrocarbons are natural gas, oil and coal.
Surface water:	Any body of water above ground, including streams, rivers, lakes, wetlands, reservoirs, and creeks.
Unconventional oil and gas:	Unconventional oil and gas resources are produced from unconventional reservoirs. Unconventional oil and gas include tight oil, oil sands, oil shale, shale gas, tight gas, and coalbed methane.
Unconventional reservoir:	Reservoirs, which require hydraulic fracturing for the extraction of hydrocarbons occurring in these reservoirs, where the permeability is less than 1 milliDarcy.

1. Hydrocarbon extraction overview

This chapter explains hydrocarbon extraction processes and discusses its effects on inland water resources. Oil and gas are important energy sources for human society, with the oil industry being the largest international industry in the world. The transportation of goods, manufacturing of plastics and fertilizers, and electricity generation all depend to a large degree on oil and gas (Robbins et al., 2014). Societies have, therefore, invested heavily in oil and gas infrastructure and equipment, such as vehicles and roads (Van Vactor 2010). However, this industry also uses substantial amounts of freshwater (Spang et al. 2014) and influences water resource quality, and as such, has a considerable impact on the world's freshwater resources (see section 2).

Although oil has been extracted since the early 1900s, it became the dominant form of energy with the discovery of many of the largest conventional oil reserves in the Middle East just before and after World War Two. Before then, coal was far more important. Since the end of World War Two, the use of oil for energy generation has been a critical factor in increased global prosperity (Van Vactor, 2010). To ensure ongoing economic development, countries tried to procure sufficient and stable supplies of oil and gas from countries with such resources or, where possible, by producing their own. This has contributed to energy crises, such as the 1973 oil embargo by oil-producing nations that triggered worldwide oil shortages (Harper & Snowden 2017).

Oil and gas derive from compressed and cooked organic matter that was buried to significant depths over millions of years and occurs in conventional and unconventional deposits (Figure 1). From the 1970s to the 1990s conventional oil was produced in surplus, after which conventional oil supplies started to decline. Since the early 2000s, alternative hydrocarbon sources in the form of unconventional oil and gas were targeted, enabled by hydraulic fracturing and horizontal drilling (Van Vactor 2010; Bilgili et al. 2020). The US leads in the extraction of unconventional resources, where it accounted for 44% of gas production in 2014 (Bilgili et al., 2020). Natural gas production in the US may more than double over the coming 30 years (Bilgili et al., 2020). Because unconventional resources step in where conventional resources are declining, there is no foreseen imminent peak in oil production (peak oil).

2. Risk and impacts on water resources

Hydrocarbon reserves are increasingly being targeted in some of the most remote and pristine areas on our planet (Morley, 2017), including the East African Great lakes area (Verheyen et al., 2016) and Amazonia (Figure 1 and Box 2: Oilfields in Amazonia). Oil production in developing countries increased over threefold from 1973 to 2008, often involving the use of controversial technologies such as hydraulic fracturing. The oil industry uses approximately 40% of the annual 52 billion m^3 of freshwater that is consumed to meet the global requirement for energy and fuel (Spang et al., 2014). With the emergence of unconventional oil and gas extraction techniques, this share is expected to rise, with dire effects on water-scarce countries (Figure 1).

<Figure 1 near here>

It is estimated that most future oil and gas projects will be situated in developing countries, which have increased energy needs as their economies grow. Although technological advances made the extraction easier and less risky, poor management and lack of oversight often led to environmental degradation and water resource pollution. Impacts on water resources occur at the exploration, extraction, and post-extraction stages of hydrocarbons. Figure 2 illustrates the main impacts for conventional and unconventional oil and gas extraction, while Tables 1 and 2 provide detailed information on the possible impacts.

<Figure 2 near here>

<Table 1 near here>

<Table 2 near here>

The negative impacts of hydrocarbon extraction on water resources are viewed as one of the most significant biophysical impacts (Rosa et al. 2018), both in terms of the effects on water quantity and water quality, while water-related negative socio-economic and biophysical impacts are also far-reaching. These impacts are discussed in detail below. As oil and gas are increasingly being extracted in biologically rich regions of the world, it will likely pose a greater threat to biodiversity, especially in areas with high aquatic biodiversity such as in South America, see Boxes 1,2 (Harfoot et al., 2018) and Africa (Verheyen et al., 2016, Box 3).

2.1 Conventional oil and gas extraction impacts

Although the effects of conventional oil and gas extraction on water resources are less than for unconventional, impacts can still be significant. Water use during conventional oil extraction is typically less than for unconventional resources (Scanlon et al., 2014), but largely depends on the geological characteristics of the reservoir. Primary recovery is used during the first stage of oil recovery when natural pressures in the oil reservoir are sufficient to bring oil to the surface. However, as reservoir pressure declines, enhanced oil recovery methods may be employed to increase oil production. Primary recovery may be followed by secondary recovery that includes waterflooding and even tertiary recovery that includes steam injection, to drive residual oil to the production wells (Parra et al., 2020). Water use during primary production is minimal, but can be significant during the secondary production phase (Scanlon et al. 2014). The additional water demand of conventional oil and gas extraction on local water resources can lead to conflicts between water users in water-stressed areas or in times of drought (Sohns et al., 2016).

In terms of water quality impacts, conventional oil and gas extraction generates wastewater in the form of produced water and spent drilling fluids. Produced water is the largest wastewater source by volume. It can contain metals, sediments, and chemicals that may be radioactive and toxic (Parra et al., 2020). Produced water disposal is a concern – if it is injected into wells for disposal or enhanced oil recovery, it may induce seismicity. The alternative is the disposal of this wastewater at hazardous waste sites or treatment at wastewater treatment plants equipped for these types of waste, which many countries are not equipped to handle.

2.2 Unconventional oil and gas extraction impacts

Of the negative environmental effects of unconventional oil and gas extraction (Esterhuyse et al. 2016), the most immediate effects are those on water resources. Because a stimulation method such as hydraulic fracturing is typically required to extract unconventional resources, it is often more water-intensive than conventional oil extraction (Kondash et al., 2018). Where one drilling well operation could consume approximately 500 m^3 of water without fracking, a fracking well consumes 20 times that amount (Goodwin et al., 2012). Water for fracking is often sourced in the vicinity of the fracking well, making local groundwater reserves a common target. In 2015 in the Eagle Ford shale, US, fracking operations consumed approximately 30% of the area's total groundwater (Steadman et al., 2015). Compared to conventional oil and gas extraction, fracking will lead to even higher localized competition between water users in water-scarce and drought-prone areas (Figure 2, Tables 1 and 2).

Next to produced water, an additional wastewater stream in the form of flowback is generated during unconventional oil and gas extraction. The chemistry of the flowback depends on the chemical makeup of the hydraulic fracturing fluid and may contain various toxic and carcinogenic organic contaminants (McIntosh et al., 2018). The water quality impacts of unconventional oil and gas extraction are therefore typically larger than for conventional oil and gas extraction. Produced water and flowback can contaminate freshwater aquifers due to poor oil and gas well integrity, or due to migration of these fluids via fracture zones. Fracking fluid and wastewater can contaminate surface waters via leaks and spills. Wastewater disposal in underground injection wells can also cause seismicity and has significantly increased induced seismicity in Canada, the US, the UK, and China, in some cases causing earthquakes as large as magnitude 5.7 (Schultz et al. 2020). The density of oil and gas wells, which are higher than for conventional oil and gas production, can also have cumulative negative effects on aquatic ecosystems (Entrekin et al., 2011; Dauwalter, 2013).

2.3 Acute impacts from spills and leaks

Marine oil spills in coastal areas often have dire effects on mangroves (see Box 1). Mangroves form a relatively small, but distinctive biome that delivers unique ecosystem services to coastal communities, and that serves as a nursery for many marine species.

<Box 1 near here>

Even though marine oil spills are more publicized, inland oil spills occur more frequently, often affect sensitive freshwater environments and have larger impacts on public health (Yoshioka and Carpenter, 2002; Kinston, 2002; Azevedo-Santos et al., 2021). The acute impacts from oil spills are more severe than the chronic impacts of extraction and processing (Etkin, 2011). Spills can occur in any phase of the process, including the extraction of crude oil and the transportation of refined fuels. During the extraction phase, oil spills tend to cause acute impacts, whereas small chronic spillages occur most frequently in the transportation phase. Given the uneven distribution in oil and gas production and consumption, oil and gas are transported over large distances using tanker trucks, rail, and, most importantly, pipelines (Michel and Fingas, 2016). As many streams and rivers are crossed by roads, freshwater environments are highly susceptible to the impacts of spills from tanker trucks (Laurence et al., 2009). These aquatic ecosystem impacts can extend over long distances from the source and affect fish, crustaceans, reptiles, birds, and mammals. Although pipelines can economically transport enormous volumes of oil over large distances, they come with an inherent risk of oil spills, often resulting in the contamination of surface waters. A review of Canadian oil leaks from pipelines revealed that spills were frequent, variable in scale, and posed a wide range of potential adverse environmental effects. Additionally, pipeline oil spills were difficult to predict, posing challenges to management and policy (Kheraj, 2020). To detect spillages, companies rely on high-tech (automatic monitoring) and low-tech techniques (pipeline walkers, helicopter patrols). In developing nations, however, and in regions with weak governments, relaxed environmental regulation increases the risk of undetected leakage. Pipelines are often targeted during armed conflicts, especially in areas with a rich oil wealth (Le Billon, 2013), and also face significant threats from vandalization and cyber-attacks (Oluwatuyi and Ileri, 2013, Dancy and Dancy, 2017), which increases leakage risks. Because of these risks, the construction of new pipelines, especially through culturally or ecologically sensitive land, is nowadays increasingly opposed.

2.4 Ecological impact on aquatic communities

The direct impacts of oil and gas extraction on biodiversity and ecosystem services include habitat loss and fragmentation, pollution, changes in water resources and flow regimes, alterations in the structure of freshwater communities (Entrekin et al., 2011, Jones et al., 2015), and changes in wildlife habitat use (O'Rourke and Connolly, 2003) (Table 1, Figure 2). Although the composition of petroleum varies greatly, crude oil is a mixture of (cyclo)alkanes and (poly) aromatic hydrocarbons (PAHs), with, to a lesser degree, sulfur- and nitrogen-containing hydrocarbons and trace metals. Several PAHs are carcinogenic and/or acutely toxic to aquatic organisms (Echols et al. 2009).

In freshwater environments, oil droplets can attach to suspended matter to form oil-particle aggregates. Even after complete clean-up of an oil spill, these can resuspend in the water column (Zhu et al., 2018). Toxic resuspended oil from oil spills, as well as flowback, produced water, and wastewater can result in wildlife mortality (Etkin, 2011). This toxicity can impact all levels of biological organization (from organism to ecosystem or landscape), reach different spatial scales (from localized to expanded regional impacts), and may continue for years (Azevedo-Santos et al., 2021). At the individual level, potential oil spill impacts include changes in the behavior, morphology, or life history of native species, while at the population level impacts include changes in the abundance and distribution of native or non-native species. At the community level, oil and gas extraction impacts can cause extirpations and species extinctions, but more commonly causes changes in species composition and diversity or abundances and interactions. These alterations can cause biotic homogenization and changes in the size and structure of food webs. At the ecosystem level, oil spills can affect and even alter entire river ecosystems. It can directly affect certain ecosystem engineers, e.g. bivalves, due to their high filtration rates, and can change primary productivity from food webs based on macrophytes to food webs based on benthic algae. Furthermore, impacts at the lower levels of biological organization may affect the higher levels, which can lead to a decrease in biodiversity and deterioration of the genetic heritage (Gomes et al., 2000).

In addition to the direct impacts, indirect threats of oil and gas exploration can exacerbate the negative impacts on ecosystem functioning and biodiversity loss. Exploratory drilling can open up new areas, leading to the expansion of logging, hunting, and human settlements, as well as the introduction of non-native species (Laurence et al., 2009). These indirect threats pose challenges in tropical forests, as they lead to deforestation, with oilfield access roads providing access to settlers and other actors who invade and clear the forest. In Ecuador, 500 km of roads were built for oil extraction by 1989, leading to 10,000 km2 of land being claimed by settlers, in addition to the entry of agribusiness, ranching, and logging (Kimerling, 2006). This is a harbinger of one of the dangers of Brazil's massive plans for oil and gas extraction in the western portion of its Amazon region (see Box 2).

<Box 2 near here>

2.5 Socio-economic impacts

Oil and gas development has profound and often long-lasting impacts on surrounding communities (Table 2). While some socio-economic benefits include increased job opportunities and improvements in infrastructure such as roads, these benefits are often gained at the expense of community cohesion, human health, and wellbeing, and local livelihoods (Appel et al., 2015; Jenkins et al., 2016; Scanlan, 2017). Existing social, political, and economic inequalities further result in an unfair distribution of benefits, risks, and harm associated with these developments. This is referred to as environmental injustice. Negative impacts disproportionately affect vulnerable and marginalized groups and communities that are least able to protect themselves (Inkpen & Moffet, 2011), such as ethnic minorities, indigenous communities, rural communities, the poor, and women, and with these vulnerabilities often intersecting (Canfield et al., 2020; Long et al., 2020).

Areas surrounding oil and gas developments experience an influx of people, drawn by the possibilities of employment and economic development. Rapid population increases lead to increased pressure on natural resources such as water and land (Ayanlade and Howard, 2016). Oil and gas extraction furthermore contribute to pollution of air, water, and land, and this pollution has implications for human health and wellbeing. Chemicals used in unconventional oil and gas extraction processes that are released into the environment may gradually contaminate water resources, with the impacts on human health only becoming apparent in the future. These chemicals have been linked to the development of cancers, birth defects, miscarriages, and other diseases and much uncertainty remains to what extent unconventional oil and gas extraction contributes to the development of these diseases (Finkel, 2016; Gorski and Schwartz, 2019). In the case of oil spills, surface and groundwater sources are contaminated, killing wildlife and fish and ruining the resource base on which local people depend for subsistence (Faber, 2020).

Poor or indigenous communities often rely on freely available ecosystem services for subsistence. Some 25% of poor rural households' livelihood resources such as firewood, medicinal plants, and food are obtained directly from the environment (UNEP, 2016; FAO, 2018). Additionally, small-scale fisheries are a major source of protein and income for the rural poor (Béné et al., 2009). When local communities lose access to wild food source areas, and when environmental pollution from oil and gas extraction and transportation exacerbate resource scarcity, it affects their food security and income generation. Particularly in water-scarce areas, access to and availability of clean water are critical community concerns. Communities downstream from such developments may experience dropping water levels in rivers, lakes, and wetlands. Falling water levels can disconnect indigenous populations from accessing subsistence lands as they are unable to reach these lands by boat (Scanlan, 2017; Westman & Joly, 2019).

2.6 Legacy impacts

Legacy impacts are long-term impacts that span over multiple generations and that are not easy to fix. Oil and gas extraction can have legacy impacts on both surface water and groundwater. On a local scale, leaking oil and gas wells can contaminate groundwater resources, which often cannot be cleaned up easily, if at all (NRC, 2013). This can lead to a permanent loss of the groundwater resource, meaning that communities must rely on other water sources or imported water over the medium term. Over the long term, communities may even be displaced because of a loss in livelihoods due to the groundwater supply loss.

On a regional scale, the abandonment of oil and gas wells, or the poor sealing of wells after well decommissioning, may lead to long-term groundwater contamination legacy issues (ANU, 2012). Davies et al. (2014) report that between 1.9% and 75% of wells from different oil and gas extraction areas worldwide, failed, but estimates are that almost all wells would eventually leak and potentially contaminate groundwater due to the mechanical failure of well casings (Bishop, 2011). Apart from contaminating groundwater resources, abandoned oil and gas wells also release methane into groundwater and the atmosphere. In the US alone, the oil and gas industry has abandoned about 3.4 million wells that were used over the past 100 plus years of drilling. These wells emitted an estimated 290 kilotons of methane into the atmosphere in 2018 alone (EPA 2021). The large number of wells that are drilled to access oil and gas resources, makes the regional legacy impact of leaking wells considerable.

Oil and gas extraction can also have vast impacts on surface water resources. If planned oil and gas drilling in the Okavango catchment contaminates the Okavango delta, it will lead to legacy contamination impacts (see Box 3: Okavango case study).

<Box 3 near here>

Similarly, legacy impacts can also be expected if current initiatives for oil exploration will lead to exploitation in the East African Great Lakes. Oil exploration is advanced in Africa’s largest freshwater reservoirs, including the rift valley lakes Tanganyika, Malawi, and, lately, Albert, threatening their unique ecosystems and biota (Verheyen et al., 2016). As these are crucial in terms of water, food, and livelihoods for millions of people, an oil spill would markedly affect the health, water supply, and food security of local communities. The remote location of these lakes impedes quick and effective reactions to oil spills and as appropriate infrastructures are currently unavailable, bringing in heavy equipment at the time of a spill would be cumbersome, logistically impossible, or prohibitively expensive. Additionally, several of these lakes have very long flushing times, which means that recovery from an oil spill could take millennia. For Lake Tanganyika, which contains about one-fifth of the world’s surface freshwater, the flushing time is ~7,000 years (Verheyen et al., 2016). Finally, these lakes form the headwaters of some of the continent's largest rivers, including the Congo, the Nile, and the Zambezi. An oil spill in these lakes, which are home to thousands of endemic species, would therefore be a global biodiversity catastrophe. An accident might deal a final blow to these ecosystems, which have already been rendered fragile by anthropogenic stressors such as overfishing, deforestation, and global warming.

Long-term legacy impacts are possibly the least studied and understood, because impact monitoring usually ceases soon after oil and gas extraction stopped. This stresses the importance for governments to consider long-term financial planning to address legacy issues while hydrocarbons are still being extracted (NAP, 2018), by investing some of the funds derived from current production to address potential future environmental issues.

3. Management of oil and gas extraction

Preventing impacts of oil and gas extraction on water resources is a very important but often neglected aspect of management. The precautionary principle, an international environmental law approach, is important to prevent negative impacts from high-risk activities, especially when considering climate change and increasing future water scarcity. The most salient example of the application of the precautionary principle is the placing of moratoria on fracking, or its outright banning in many countries (Esterhuyse et al., 2019). This principle is also especially important for groundwater resource protection because polluted groundwater resources often cannot be remediated. The precautionary principle should be used in conjunction with risk management tools, such as environmental impact assessments (EIAs), strategic environmental assessments (SEAs), water resource baselines, and the regulation of the oil and gas industry, to minimize negative impacts (see Box 3: South Africa case study).

Whereas EIAs assess the impacts of oil and gas development on a project level, SEAs assess its cumulative impacts in a regional context (Esterhuyse, 2018). EIAs must be independent to ensure evidence-based decision-making that considers and addresses any environmental and societal damage that may ensue from extraction, including national or ethnic conflicts.

Baseline studies provide information on water resources before oil and gas extraction starts. Baseline data on existing water use can ensure that water uses are considered and protected before allocating water resources for extraction, while baseline water quality information alert regulators to contamination events, which can also be used to determine rehabilitation targets (Esterhuyse et al. 2019). Baselines are indispensable for establishing a legal basis for proving contamination, identifying the party responsible for the contamination, or for a company to refute a contamination claim (Esterhuyse et al., 2019).

A very important government tool to minimise impacts on water resources is regulations (Esterhuyse et al. 2019). The most effective regulatory framework includes both ‘hard’ command-and-control regulations and ‘soft’ market-based and voluntary regulations that are effectively enforced. Enforceable regulations contain provisions that establish criminal liability for cases where regulations are violated, commonly known as environmental crime. Where regulations are contravened, fines or sanctions can be imposed, for example, in 2021 Shell was ordered to pay over $111 million for water contamination in the Niger Delta (BBC, 2021). Regulations should also require public disclosure of the oil and gas operations. Disclosed data should be stored in publicly accessible databases to allow for independent scientific review of data by government, academia, and the private sector, which will allow for timely and appropriate adaptive management and the amendment of regulations as necessary.

Once contamination has occurred, clean-up and mitigation are required to minimize the negative effects on water resources. Here, the ‘polluter pays’ (see above example) and ‘cradle-to-grave' principles are useful for holding the polluting companies liable, assuming that the polluter can be identified. However, even if companies pay for remediating water resources, the remediation of groundwater pollution (which mostly includes pump-and-treat and in-situ bioremediation methods) is often unsuccessful (NRC 2013), which is why groundwater pollution should be prevented at all costs. Ogoniland in the Niger Delta, home to the third-largest mangrove ecosystem in the world (see Box 1), is one of the most striking examples of groundwater pollution by oil and its lack of remediation success. Here, the groundwater of 69 sites covering around 1000 km^2 was severely contaminated with oil, mostly from leaking pipelines. Several years after these sites were contaminated, and after various clean up attempts, they are nowhere near remediated (UNEP, 2011; Gundlach et al., 2021). Remediation of surface water, which is also not always successful, includes biological, chemical, physical and chemical, thermal and heat, electric and electromagnetic, acoustic, and ultrasonic treatment methods (Ossai et al. 2020).

Establishing protected areas also protects regional sensitive aquatic environments. However, the difficulty in protecting aquatic environments from hydrocarbon extraction and its often significant impact on the livelihoods of riparian residents is globally evident. Numerous incidents worldwide, such as spills from drilling sites, lead to local claims of water pollution and health effects on human communities and their livestock.

Rather than opting for sustainable development strategies, governments often circumvent legal barriers by issuing hydrocarbon exploration and extraction permits in sensitive and even protected areas (see Box 1: Niger Delta and Box 3: Okavango case study). This negatively affects freshwater habitats that are the source of livelihoods for riparian populations and that contribute to sustainable economic development. The problem is most pronounced where governments want to quickly build up their state revenues, while a lack of resources to manage protected areas further compounds the issue. It is also important to note that these protected areas represent only a fraction of the scientifically identified priority biodiversity areas.

To avoid the prioritization of short-term gains over the long-term sustainable livelihoods of people living in oil and gas target areas (La Vina et al. 2010), governments should develop economically and ecologically viable extraction strategies in collaboration with regional stakeholders and scientists throughout the decision-making process. Norway is an example of where civil society influences petroleum governance to ensure sustainable development (Overland, 2018) Community initiatives to conserve natural habitats during hydrocarbon extraction can complement central government initiatives. Decentralized management of sensitive and protected areas is an obvious, if not a more viable solution, given the difficulties that the respective responsible central agencies sometimes face.

Sound environmental principles, such as the development of specific guidelines for public participation, should be incorporated during protected area management planning. Implementation of these principles requires unfettered access to information, including maps, relevant rules and regulations; and results on energy resources within protected areas. Only with these kinds of tools can local communities curb their governmental aspirations of sudden wealth, and prevent discrimination, dispossession, and long-term health problems.

4. The future of oil and gas extraction

The energy sector is the source of around three-quarters of greenhouse gas emissions today (IEA, 2021) and holds the key to averting the worst effects of climate change, which is perhaps the greatest challenge humankind has faced. Climate change and its effects are inextricably linked to water resources (Stephens et al., 2020), leading to sea-level rise, climate extremes with more severe droughts and floods, irreversible effects on aquatic ecology, more water scarcity, and massive economic loss (Betts et al., 2018). Sea-level rise could in turn further endanger mangroves and also lead to coastal freshwater aquifers being intruded by saltwater, further limiting freshwater supplies. To limit such negative effects, the long-term increase in average global temperatures must be limited to 1.5 °C, as required under the international Paris Agreement, by achieving net-zero carbon emissions by 2050 (IEA, 2021).

The path to net-zero emissions by 2050 requires an immediate and massive deployment of all available clean and efficient energy technologies. Reaching net-zero emissions by 2050, with a world economy in 2030 being some 40% larger than today, requires a worldwide increase in energy efficiency, emissions reductions from the energy sector in CO_2, and a drop of 75% in methane emissions from fossil fuel production (IEA, 2021).

Future energy requirements predict that energy demand reaches a plateau from around 2030 onwards and that gas will become increasingly prominent over the coming years (McKinsey, 2021). It is predicted that gas will fuel the energy transition and overtake oil to become one of the world's largest primary energy sources by 2025 (IEA, 2019). The European Union sees gas as a critical transition to renewable energy and is of the view that substituting coal and oil with gas could help to reduce carbon emissions (EC, 2012, IRENA, 2018). Although large-scale investment in natural gas may help in transitioning from coal and oil to renewables, gas can only temporarily fulfil this role because it still emits CO_2 and CH_4. Over the long term, natural gas extraction can therefore work against reaching the climate goals (Gürsan and de Gooyert, 2020).

Oil majors are already significantly increasing the share of gas in their portfolios, and despite fossil fuel extraction having to end to avoid catastrophic climate change (IEA, 2021), continued investment in new gas developments is still expected. It is however of the utmost importance that any new oil and gas developments limit negative water resource impacts. Considering climate change (IPCC, 2021) and biodiversity loss (Dasgupta, 2021), governments must also in the long run limit CO_2 and CH_4 emissions by moving away from fossil fuel extraction, and must pursue sustainable engagements with Nature that enhances our wellbeing and that of our descendants.

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Tables

Table 1: Biophysical impacts of conventional and unconventional oil and gas extraction present in landscape

Activity	**Phase**	**Aspect**	**Possible positive impacts**	**Possible negative impacts**
Conventional oil and gas	**Exploration phase**	Surface water and vegetation	● Possible new species identified	***Seismic exploration:*** ● Increased sediment load in rivers due to increased erosion from seismic exploration (A) ● Seismic vibration affects freshwater invertebrates and vertebrates (e.g., fish) (A) ***Drilling fluid and produced water discharge, leakage or spill:*** ● Drilling fluids leaching into surface water via groundwater or via overland flow from surface spillages contaminate rivers, pans, lakes (A) ● Diesel pollution reduces abundance and diversity of freshwater organisms (e.g., invertebrates and fish) (A) ***Infrastructure development (seismic lines, road development, river crossings, limited wellpad development):*** ● Increased sediment delivery to river may impact critical habitats (e.g., fish spawning habitat), cause turbidity and reduce visibility for predators (A) ● Native species richness and abundance tend to decrease, and the introduction, establishment and spread of nonnative species are favored (A/C) ● Disruption of fish migration due to increased sedimentation, pollutants, turbidity and fragmentation (from road crossings in rivers) (A) ● Road construction to remote areas allows entry of deforesters and consequent vegetation loss ● Declined plant biodiversity, habitat loss and fragmentation (for drill site and road construction) (A) ● Favors the introduction, establishment and spread of nonnative species (A/C) ● Surface spills of hazardous material (drilling fluid and produced water) impacting on vegetation (A) ***Water sourcing from rivers for drilling:*** ● Reduced streamflow in perennial rivers (A) ● Loss of critical habitats (e.g., refuge and spawning) in rivers and lakes (A) ● Loss of river migratory passages lead to loss of mobility, reduced food availability, fragmentation and isolation of fish assemblages (A) ● Water quality changes, heat death of fishes in isolated pools and lakes, higher contaminant impact on fish during low stream discharge or isolation periods (A) ● Reduced fish fitness and health due to increased predation, intra- and interspecific competition and crowdedness in isolated pools (A)
		Groundwater	● Develop a better understanding of the deeper geology and geohydrology	***Unknowns:*** ● Difficult to identify aquifers at risk for contamination since deeper geology and structures are unknown (C) ● Artesian basin conditions may cause upward migration of formation water (C) ***Saline water produced during drilling:*** ● May contaminate aquifers via well or via reserve pit leak (A/C) ***Drilling fluid and produced water discharge, leakage or spill:*** ● Drilling fluids (e.g., diesel) leaching into groundwater or via overland flow from surface spillages contaminate rivers, pans, lakes (A/C) ***Water sourcing from groundwater for drilling:*** ● Reduced groundwater levels and quality (A/C)

Activity	**Phase**	**Aspect**	**Possible positive impacts**	**Possible negative impacts**
		Seismicity	● Not known	***Increased seismicity during drilling:*** ● Level of seismicity may increase, but extent of increase is uncertain (A/C) ● Possibility to observe or induce and/or trigger a strong seismic event (A/C)
Conventional oil and gas	**Extraction phase**	Surface water and vegetation	● Possible new species identified	***Wastewater and oil discharge to water bodies via leaks and spills:*** ● Flowback and produced water contaminate rivers/lakes (A/C) ● Water quality changes in isolated pools and lakes, heat death of fishes in isolated pools, higher impact of contaminants on fish during periods of low stream discharge or isolation (A) ● Reduced fish fitness and health due to increased predation, intra- and interspecific competition and crowdedness in isolated pools (A) ● Reserve pit leaks may lead to contamination and/or mortality of fish and waterbirds (A) ● Changed community structure and/or high mortality of organisms (e.g., zooplankton, macroinvertebrates, fish, water snakes, waterbirds) via oil spills from tanker trucks and pipelines (A/C) ● Spills from pipelines and boats cause direct impacts on mangroves forests (e.g., loss of native mangrove growth and favoring nonnative plants), and indirect impacts on other organisms that inhabit these ecosystems (e.g., crustaceans and fish) (A) ***Infrastructure development (roads, river crossings, extensive wellpad development, wastewater treatment):*** ● Fragmentation of habitat and reduced colonization and fish diversity (C) ● Truck traffic accelerates erosion, leading to changes in sediment delivery to river, reduced habitat and visibility, lower fish productivity and fitness, lower levels of recruitment and possible effects on the food web (A/C) ● Changes in macroinvertebrates diversity and density, and in fish assemblage structure (A) ● The introduction, establishment and spread of nonnative species (A/C) ● Impacts on vegetation same as for the exploration phase but on a larger scale, and: ● Decreased habitat complexity and loss of ecosystem services (A/C) ***Land-use changes:*** ● Increased sediment delivery to river may impact critical habitats (e.g., fish spawning habitat), cause turbidity and reduce visibility for predators (A) ● Increased sediment in stream/river can contribute to eutrophication (A) ● Loss of fish, amphibians and invertebrates diversity, and disruption of fish migration due to increased sedimentation, pollutants, turbidity and fragmentation (from road crossings in rivers) (A) ● Land use change could isolate rivers, pans and lakes, resulting in genetic isolation and reduction in number of refugia (C) ● Displacement and decrease in richness/abundance of native species (A) ● Favors the introduction, establishment and spread of nonnative species (A/C) ***Water sourcing from rivers for drilling:*** ● Removal of water from rivers may affect hydrology of water resources, change the interactions of freshwater communities and ecosystem functions (A) ● Reduced streamflow in perennial rivers (A) ● Loss of critical habitats (e.g., refuge and spawning) in rivers and lakes (A)

Activity	Phase	Aspect	Possible positive impacts	Possible negative impacts
				● Loss of river migratory passages lead to loss of mobility, reduced food availability, fragmentation and isolation of fish assemblages (A) ● Decrease in resource connectivity, reduction in abundance and diversity of invertebrates and fish, increase in tolerant species (A) ● Groundwater abstraction leads to loss of baseflow to springs, loss of hyporheic flow, loss of refuge habitat, water quality and volume changes (C)
		Groundwater	● Same as for exploration phase	● Same as for exploration phase and: ● Larger scale sourcing of water from local aquifers may induce aquifer connectivity, change groundwater levels, cause contamination and seismic activity. ● Large scale surface activities contaminate aquifers via surface water-groundwater interaction. ● Large scale wastewater poses serious challenges if not managed properly. ● Poor well integrity may cause leakage of gas or fluids and groundwater contamination.
Conventional oil and gas		Seismicity	● Not known	● Same as for exploration phase but on a larger scale
	Post-extraction phase	Surface water and vegetation	● Risk of surface water contamination lowers	***Wastewater and oil discharge from leaks and spills:*** ● Long-term impacts of contamination on rivers, pans, lakes (C) ● Unknown impact of specific chemicals on individual species or on freshwater communities (A) ● Reduced habitat quality, reduced fish fitness and health and increased freshwater mortality due to exposure to toxic substances (A/C) ● Reduced availability of food sources (e.g., invertebrates) (A) ● Bioaccumulation of toxic substances in the food web (A) ***Poor oil well integrity and well leaks:*** ● Possible contamination over long-term via surface water/groundwater connectivity if oil wells leak over long-term (A/C/L) ***Disturbed area:*** ● Continued stream/river degradation (C) ● Susceptibility to nonnative species invasion may continue for years (C) ● Resuspension of pollutants after clean-up (C) ● Migration of polluted ground- and/or surface water pollution to the rooting zone – vegetation die-back (A/C) ● Success of vegetation rehabilitation uncertain (C/L) ● Continued habitat fragmentation, due to poor upkeep of existing infrastructure, roads or nonnative invasive species control (C) ● Continued loss of plant biodiversity and ecosystem services (A) ● Possible establishment and spread of nonnative plants (A/C) ● Illegal trade of endangered plants due to access roads (A)
		Groundwater	● Pollution risk in the area where fracking is ceased, lowers	● Aquifer pollution from oil production may only surface years after a pollution incident (A/C/L) ● The extent of possible long-term contamination in freshwater aquifers could not be predicted (A/C/L) ● Inability to rehabilitate contaminated aquifers in complex geology (physically and economically) (A/C/L) ● Well abandonment and long-term monitoring may be problematic (A/C/L)

Activity	Phase	Aspect	Possible positive impacts	Possible negative impacts
				● Oil and gas well casing failure and leakage may pose long term legacy issues and lead to inevitable groundwater contamination (A/C/L)
		Seis-micity	● Not known	● Possible post-extraction seismicity
Unconventional oil and gas	**Exploration phase**	Surface water and vegetation	● Possible new species identified	***Seismic exploration:*** ● Same as for conventional oil and gas exploration ***Drilling fluid, fracking fluid and wastewater (produced water and flowback) discharge during fracking pilot well testing:*** ● Drilling fluids, fracking fluids, wastewater leaching into surface water via groundwater or via overland flow from surface spillages contaminate rivers, pans, lakes (A/C/L) ● Pollution reduces abundance and diversity of freshwater organisms (e.g., invertebrates and fish) (A/C) ***Infrastructure development (road development, river crossings, limited wellpad development, seismic lines):*** ● Impacts on surface water and vegetation same as for conventional oil and gas exploration, and: ● Surface spills of hazardous fluids (drilling fluid, fracking fluid and wastewater [produced water and flowback]) during fracking pilot well testing can cause impact on vegetation (A) ***Water sourcing from rivers for UOG extraction:*** ● Same as for conventional oil and gas exploration, but on larger scale, since fracking uses much larger volumes of water ***River sand mining to obtain proppant for fracking:*** ● Increased surface water turbidity (A) ● Removal of sand may impact on freshwater organisms in alluvial aquifer/hyporheic zone (A) ● Increased sediment deposition in rivers could increase turbidity and limit habitat and food available to invertebrates and fish (A)
		Groundwater	● Develop a better understanding of the deeper geology and geohydrology	***Unknowns:*** ● Same as for conventional oil and gas exploration ***Drilling in shale:*** ● Possible shale instability with associated borehole problems such as hole collapse, stuck equipment, plastic flow, fracturing, circulation loss and poor well control may cause contamination (C) ***Saline produced water during CBM extraction:*** ● Large quantities of saline water produced by CBM contaminate aquifers if aquifers and coalbed formations co-occur (A/C/L) ***Hydraulic fracturing pilot testing*** ● Groundwater contamination if hydraulic fracturing is allowed during the exploration phase, both for coalbed methane and shale gas formations (A/C/L)

Activity	Phase	Aspect	Possible positive impacts	Possible negative impacts
		Seis-micity	● Not known	***Increased seismicity:*** ● Same as for conventional oil and gas exploration but on a larger scale
	Extraction phase	Surface water and vegetation	● Possible new species identified	***River sand mining to obtain proppant for fracking:*** ● Same as during exploration phase but on larger scale ***Drilling fluid, fracking fluid and wastewater (produced water and flowback) discharge during fracking:*** ● Various sources of pollutants may impact rivers on a much larger scale than exploration (A) ● Increase of sediment and contaminants may impact freshwater organisms physiology or behavior and alter ecological community interactions (A/C) ***Infrastructure (Extensive road development, river crossings, extensive wellpad development, wastewater treatment plants):*** ● Impacts on surface water and vegetation same as during conventional oil and gas extraction, but on larger scale ***Water sourcing from rivers for UOG extraction:*** ● Same as during exploration phase but on larger scale
Unconventional oil and gas		Groundwater	● Using safer chemicals (e.g. gasses or plant-based oils) ● Using green in fracking	● Same as for exploration phase and: ● Large scale sourcing of water from local aquifers may induce aquifer connectivity, change groundwater levels, cause contamination and seismic activity (A/C/L) ● Shale drilling over large regional areas may cause diffuse contamination (A/C/L) ● Surface activities over large regional area contaminate aquifers via surface water-groundwater interaction (A/C/L) ● Wastewater produced in large quantities during extraction poses serious challenges if not managed properly (A/C/L) ● Poor well integrity may cause leakage of gas or fluids and groundwater contamination, also for CBM (A/C/L) ● Large scale extraction of water from CBM causes geology and aquifer deformation, subsidence, decreased baseflow and reduced springflow (A/C/L)
		Seis-micity	● Not known	***Increased seismicity:*** ● Same as during conventional oil and gas extraction but on larger scale
	Post-extraction	Surface water (quality) and vegetation	● Risk of surface water contamination lowers	***Drilling fluid, fracking fluid and wastewater (produced water and flowback) discharge during fracking:*** ● Same as for conventional oil and gas post-extraction phase and: ● Not all chemicals used in fracturing fluids are known, therefore unknown chemical impacts are uncertain(A/C/L) ● Pollutants may impact rivers (A/C/L) ● Possible contamination via groundwater pathway due to interconnected resources (A/C) ***Disturbed area:*** ● Surface water and vegetation impacts same as for conventional oil and gas post-extraction

Activity	Phase	Aspect	Possible positive impacts	Possible negative impacts
		Groundwater	● Pollution risk in the area where fracking is ceased, lowers	● Aquifer pollution from deep shale layers may only surface years after a pollution incident (A/CL) ● The extent of possible long-term contamination in freshwater aquifers could not be predicted at this stage (A/C/L) ● Country/territory not able to rehabilitate contaminated aquifers in complex geology (physically and economically) (A/C/L) ● Well abandonment and long-term monitoring may be problematic (A/C/L) ● Oil and gas well casing failure and leakage may pose long term legacy issues and lead to inevitable groundwater contamination (A/C/L)
		Seismicity	● Not known	● Same as for conventional oil and gas post-extraction but on larger scale
Notes			A = Acute impact, C = Chronic impact, L = Legacy impact	
References			Azevedo-Santos et al. *in press*; Couceiro et al. 2010; Dauwalter 2013; Duke 2016; Entrekin et al. 2011; Esterhuyse et al. 2016; Etkin 2011; Fefilova 2011; Harfoot et al. 2018; Jones and Pejchar 2013; Jones et al. 2015; Laurance et al. 2009; Masnik et al. 1976, McCleneghan et al. 2002; O'Rourke & Connolly 2003; Osborn et al. 2011; Pring and Polunin 2010; Ramirez Jr. 2010; Song et al. 2008; Trail 2006.	

Table 2: Water-related socio-economic impacts of conventional and unconventional oil and gas extraction

Socio-economic impacts for oil and gas extraction during exploration, extraction and post-extraction			
Activity	**Phase**	**Possible positive impacts**	**Possible negative impacts**
	Population	● No water-related impacts indicated in literature	● Short- and medium-term population influx place pressure on natural and social environment (e.g., water resources and water & sanitation infrastructure) (A)
	Economic	● Infrastructure development (e.g., roads, water, sanitation)	● “Boom-town” effect”: pressure on existing infrastructure and social services (e.g., water and sanitation); pressure on municipal services (i.e., wastewater management) (A) ● Decline in tourism potential stemming from land-use changes, degradation of pristine environments, biodiversity loss, and reduced water quality (A/C)
	Agriculture and food security	● No water-related impacts indicated in literature	● Diverting scarce water resources from agriculture to oil and gas interests (A) ● Long-term impacts from dust pollution, water shortages and quality on crop production are uncertain (C) ● Land-use changes affect availability and productivity of agricultural land (C/L) ● Chemicals used in extraction may impact reproductive health of animals (C/L) ● Rural livelihoods affected by reduced access to, and availability of, wild food sources (e.g., fish) (A/C) ● Damage to agricultural land from oil spills (A/C)
	Health and social well-being	● No water-related impacts indicated in literature	● Naturally occurring radioactive materials from produced water can have health implications (A/C) ● Water quality issues may contribute to increased risk of chronic diseases (e.g., cancer and asthma), especially in vulnerable groups (children and elderly) (C/L) ● Risk of reproductive health issues uncertain (C/L) ● Psychological impacts: perceived health risks, frustration, and anxiety over nuisances such as increased traffic and noise (A/C) ● Social conflict: between community members; community and local/ national government; community and oil and gas companies (A/C) ● Loss of access to cultural sites and rituals (i.e., baptisms in rivers) (A/L) ● Increased risk of injury and death (i.e., from accidents and oil spills) (A/C)

	Population	● Population decline reduces pressure on fragile natural environments and scarce resources	● No water-related impacts indicated in literature
	Economic	● No water-related impacts indicated in literature	● No water-related impacts indicated in literature
	Agriculture and food security	● No water-related impacts indicated in literature	● Land unsuitable for farming after oil and gas resources are depleted due lingering impacts on soil, and water quality and quantity (L) ● Declining food security (A)
	Health and social well-being	● No water-related impacts indicated in literature	● Lingering health issues (e.g., cancer) (L) ● Birth defects as a result of exposure to mutagenic chemicals (L)
Notes		A = Acute impact, C = Chronic impact, L = Legacy impact	
References		Anderson & Theodori, 2009; Anderson, 2018; Canfield et al., 2020; Faber, 2020; Jacquet, 2014; Esterhuyse et al., 2016; Redelinghuys, 2016; Schneller et al., 2020	

Important case studies (to be included as boxes, approximate positions indicated in the body text)

Box 1: Oil in mangroves

Mangroves form a relatively small, but distinctive biome that delivers unique ecosystem services to coastal communities, and that serves as a nursery for many marine species. Oil contamination from ship transportation spillages and accidents during exploitation and pipeline transport, has severely affected these ecosystems (Duke, 2016). Mangroves often occur within large bay areas in tidal areas and river mouths in the tropics and subtropics, where important ports have been and are being constructed. The intense movement of large ships increases the chances of both acute accidental oil spills and smaller oil leaks. Additionally, mangroves are found within several of the world's main hydrocarbon extraction sites, such as the Persian Gulf, the Gulf of Guinea (including the Niger delta), the Caribbean Sea, and the Gulf of Mexico. Mangrove ecosystems are extremely vulnerable to oil contamination, particularly to large acute oil spills, but also to chronic oil contamination incidents. Understanding and distinguishing synergistic acute and chronic responses, as well as the singular effects of contamination, and negative impacts that stifle mangroves, are all essential to predict the ecological consequences of spillages more accurately, and for modeling subsequent impact and recovery.

Over the last few decades, large oil spills in and around the Port of Paranaguá in southern Brazil severely impacted mangroves. In 2001, the oil tanker Norma leaked 392,000 liters of naphtha, contaminating 3,000 m² of the Paranaguá bay, while a leaking Petrobras pipeline released 4,000 liters of diesel oil into the Caninana stream. The pipeline leak damaged the local fauna and flora (including mangroves) and led to the prohibition of fishing. In 2004, the Vicuña vessel exploded in the port and released millions of liters of oil and methanol into the bay. This contamination severely damaged the environment, while locals whose income depended on fishing, were compromised during fishing prohibitions. In the same year, a train derailing released 4,000 liters of fuel into the Caninana stream, while a Petrobras truck collision released 30,000 liters of oil into the Padre and Pinto rivers, with all these pollutants ultimately reaching the mangroves. All these acute oil spills occurred within only five years and affected the same mangrove areas of the Paranaguá, Antonina, and Guaraqueçaba bays.

Nowhere on earth are the effects of careless oil exploitation in mangrove areas more visible than in the Niger Delta (Nigeria). This ecologically sensitive delta contains the largest section of mangroves in Africa, but is also rich in oil and gas resources (Ayanlade and Howard, 2016). Oil and gas production in this region causes some 300 oil spills a year, with leaking pipes, and toxic waste leaching into groundwater from unlined pits, killing fish and wildlife and making it hard to grow crops (Faber, 2020). The Nigerian government has committed many human rights abuses against people protesting the destruction of the delta by the oil and gas industry (Wong, 2020).

Over the last 6 decades, over 200 prominent oil contamination incidents were reported to have negatively affected mangroves across the world. Together, these account for at least 5 million tons of oil that have been released upon up to 2 million ha of mangrove, killing or altering over 126,000 ha of mangrove flora (Duke, 2016). With less than 15 million ha of mangrove cover left as of 2020, this renders mangroves as one of the biomes most affected by the oil and gas industry. However, given the lack of reporting, these are probably grave underestimates. Oil spills' effects on mangroves can be measured by calculating the total and relative areas of dead vegetation post oiling. Such data have however only been reported on a relatively small number of incidents. This is mostly due to incomplete or unavailable data on oil spill impacts and a global disparate bias in terms of large regions and countries. The biggest data gap on indirect long-term contamination, is chronic and diluted leaks in or near large ports and extraction platforms and their sublethal effects in terms of complex animal and plant ecological interactions. Abnormal changes in the condition of either plants or animals will affect other organisms and abiotic parameters and conditions. Small and large crustaceans, such as crabs, modulate the availability of resources to other species by changing ecosystem components (Jones et al., 1994), and thus provide many ecosystem services, including burrowing that improves sediment aeration and nutrient turnover and enhances water exchange, amongst others (Duke, 2001). To redress ineffective oil spill reporting in mangrove ecosystems, Duke (2016) recommends updating operational planning and action standards, highlighting that selective trials during a spill are an opportunity to rehabilitate contaminated mangroves that can guide future clean up responses. Such data must be publicly available.

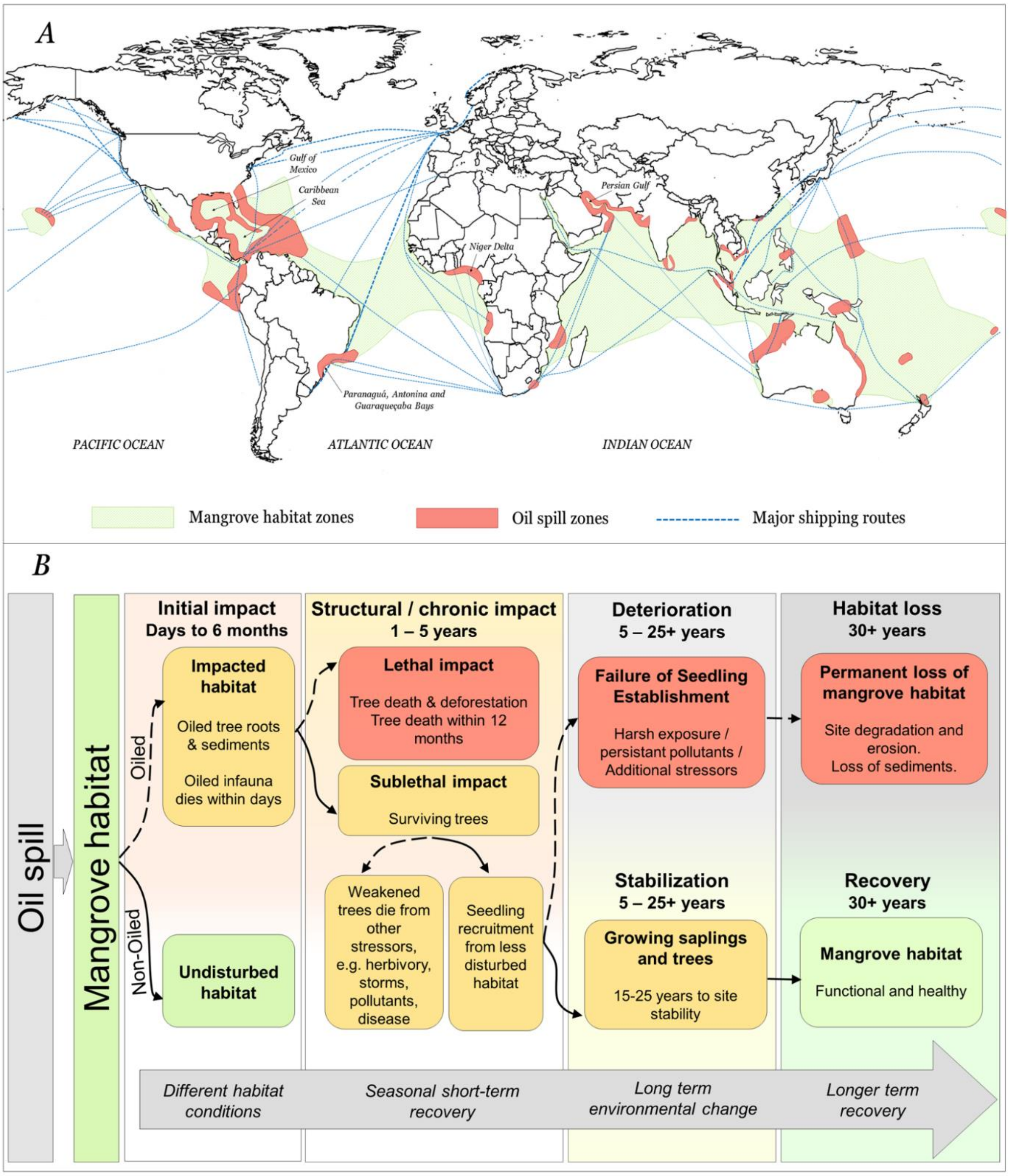

Figure 1-1: A Mangrove habitat zones, major shipping risk routes and oil spill zones (adapted from Duke 2016) and B) Schematic diagram showing the effects of large oil spills on mangrove habitat (adapted from Duke, 2016). (Image source: S Esterhuyse)

Box 2: Oilfields in Amazonia

Oil extraction has been particularly harmful to tropical forests and aquatic ecosystems of the Amazon Basin (Martínez et al., 2007; Yusta-García et al., 2017). In the upper reaches of the Amazon, in Ecuador and Peru, 12.1 million liters of produced water per day, 60 thousand liters of suspended oil per day, and large volumes of toxic mud have been released since 1990 (Martínez et al., 2007; Yusta-García et al., 2017). Instead of pumping the produced water, which contains salts, heavy metals, and other toxins, back into the wells, it was released into the rivers (Kimerling, 2006). The Trans-Ecuadorian pipeline, which connects the main production site of Lago Agrio (Ecuador) with the Pacific Ocean, also leaked approximately 73 billion liters of oil between 1964 and 1993. This represents 1.8 times the volume of the better-known 41-billion liter Exxon Valdez oil spill (Kimmerling, 2006; Sebastián and Hurtig, 2004). In 1989, feeder pipelines were leaking 5,400 liters per day (Sebastián and Hurtig, 2004).

Major oil spills however still occur in this region, such as in the Coca River in 2009, 2013, and especially in 2020, when a 2.5 billion liter spill impacted the Kichwa Indigenous people (Koenig, 2021; Ricci, 2021). These operations also seriously degraded the fisheries in Ecuador's Napo and Coca Rivers, and what locals described as a 'splendid' variety of fish in these two major river basins, was essentially destroyed (Kimerling, 2006). Amazonian fish are particularly sensitive to oil spills because many species have evolved adaptations to oxygen-poor water, leading them to come to the surface where they would encounter floating oil (Almeida-Val et al., 1999). These fish include the pirarucu or paiche (*Arapaima* spp.) air-breathing species and specially-adapted gilled species that exploit the oxygen-rich film at the water surface (Val and Almeida-Val, 1999). Salts from produced water also significantly alter regional saline concentrations (Moquet et al., 2014), and act as invisible barriers blocking fish migrations (Kimerling, 2006). The oil is not only toxic to fish (Sadauskas-Henrique et al., 2016) but also reduces the abundance and diversity of aquatic invertebrates, as shown by studies of spills near Manaus, Brazil (Couceiro et al., 2006, 2007). This undermines the base of food chains that support fish populations.

Even though Brazil already suffered significant oil and gas extraction environmental impacts, including from the upstream Ecuadorian and Peruvian operations, it still plans large-scale oil and gas extraction in the "Solimões" region (Brazilian for the Upper Amazon River, upstream of the confluence with the Rio Negro at Manaus) (Consórcio PIATAM/COPPETEC and EPE, 2020). A relatively small extraction site has operated since 1988 in this area at Urucu (purple areas in Figure 1.1). Expanding these operations within the Solimões region would however affect an area of 740,946 km^2, which is larger than the US state of California (Figure 2-1).

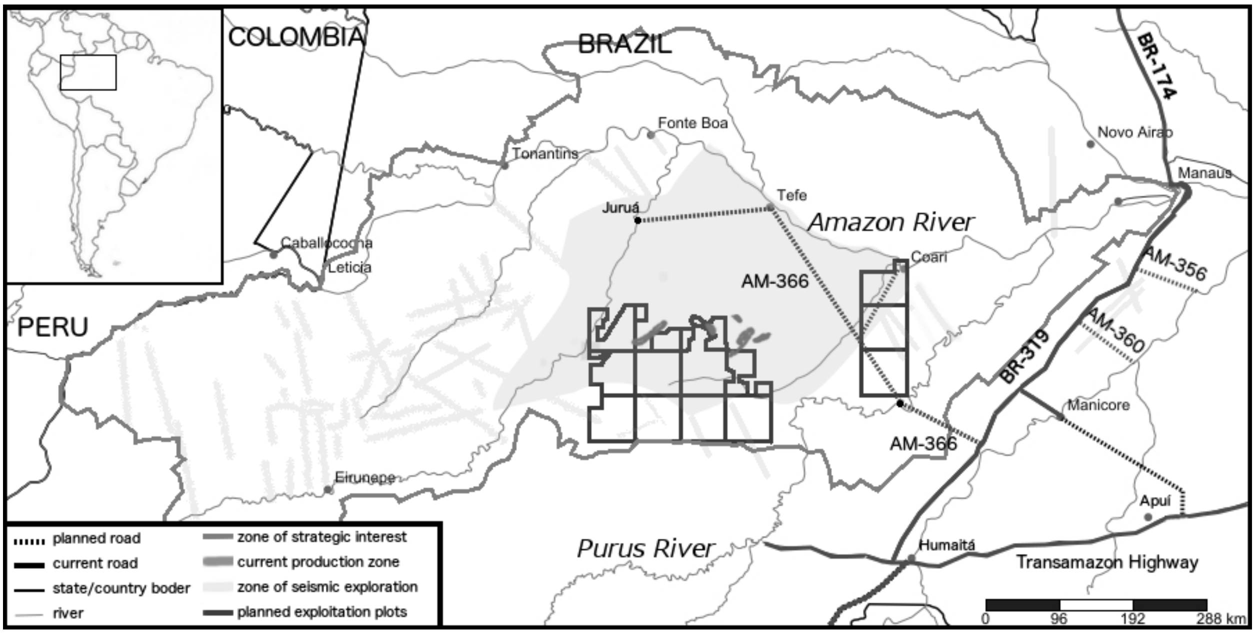

Figure 2-1. Map of oil and gas drilling blocks in the state of Amazonia, showing the current production zone and the region where seismic surveys have already taken place. Here, around 185,000 km of seismic surveys were performed before 2019 (Consórcio PIATAM/COPPETEC and EPE, 2020). The project's 'zone of strategic interest' is larger than the US state of California. The controversial BR-319 and the planned AM-366 highways would provide deforesters access to the vast area of intact rainforest west of the Purus River (Fearnside and Graça, 2006). Oil block connections to this road would likely spread deforestation throughout the Trans-Purus region (Fearnside, 2020a). (Image source: M Van Steenberge).

Currently, extraction sites at Urucu have no road access and are treated like oil platforms at sea (the "platform" model). The lack of roads has prevented settlement, land grabbing, and deforestation. With possibly thousands of wells to be drilled in the Solimões expansion project, road access would however be much cheaper. Oil companies will likely pressure the government to connect project areas to major roads, despite this not being part of the official project plan. A connection to the AM-366 highway that will connect the BR-319 (Manaus-Porto Velho) highway to Tefé, Coarí, and Juruá (Figure 1.1), is most likely.

The first oil extraction rights, located on the planned AM-366 route, have already been sold to Rosneft (DNIT, 2020), the Russian oil company accused of causing over 10,000 annual oil spills worldwide (The Guardian, 2015). Oil spills and leaks from pipelines connecting wells to central hubs and from there to Coarí via larger pipelines, are an inherent risk. The Solimões project itself could, however, incentivize the AM-366 road construction, where an illegal 'branch' road already exists along the first stretch of the planned route (Fearnside et al., 2020). Such road access would initiate uncontrolled deforestation (Fearnside, 2017) and land grabbing (Ferrante et al., 2021). At risk is Brazil's last major block of intact Amazon forest: the Trans-Purus region between the Purus River and Brazil's border with Peru (Fearnside, 2020a,b). The environmental services of the Trans-Purus forest not only curb global warming and maintain biodiversity, but also maintain water-cycling that supplies rainfall to São Paulo and other major Brazilian population centers and neighboring countries (Fearnside et al., 2020).

Box 3: Different approaches to water resource protection during oil and gas extraction in water-scarce areas of Southern Africa

There are many similarities between the Namibian Okavango and South African Karoo oil and gas extraction areas - both are water-scarce and in both cases, locals depend extensively on groundwater resources. The Namibian Kavango basin also has the same geology and depositional environment as the South African Karoo basin and is an extension of the South African Karoo Supergroup (Catuneanu et al 2005; Werner 2006). The approaches towards managing and protecting the scarce water resources of these two areas, however, differ widely and are discussed below.

Case study 1: Okavango

Reconnaissance Energy Africa (ReconAfrica), a Canadian oil and gas company, holds a license to explore both conventional and unconventional oil and gas over an area of approximately 35,000 km2 in the northern parts of Namibia and Botswana (Tan, 2021), Figure 3-1. These areas include the Namibian headwaters of the Okavango delta and the Kavango-Zambezi transfrontier conservation area (KAZA). The KAZA has one of the most diverse ecosystems on the planet, borders 3 national parks, and covers 11 community conservancy concessions. A world heritage site that lies within ReconAfrica’s PEL001 exploration area, Tsodilo Hills, was excluded from their license area in 2021 after intervention by UNESCO (UNESCO, 2021).

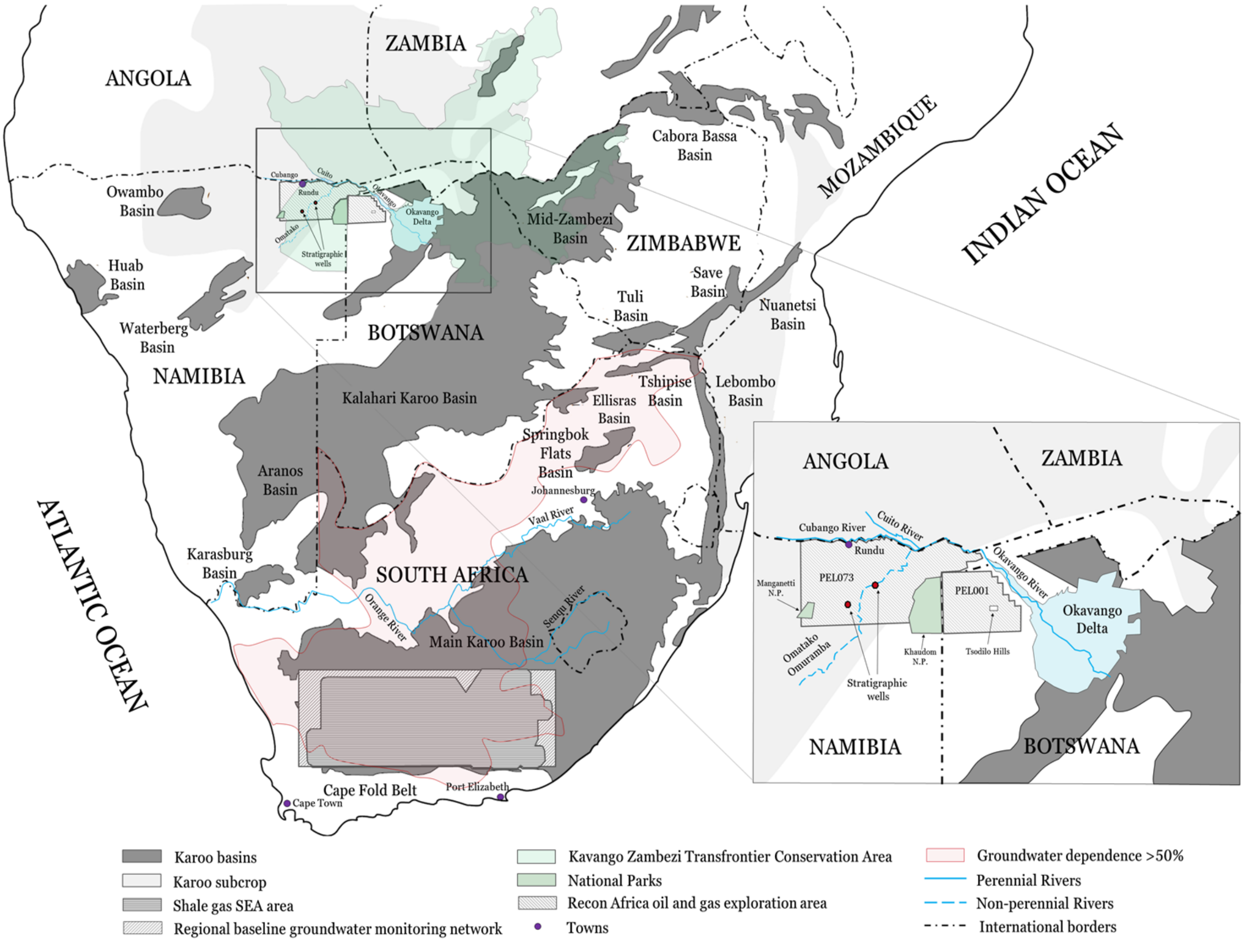

Figure 3-1: Map of Southern Africa with the South African Karoo and Okavango delta case studies, showing relevant rivers and geological basins (Image source: S Esterhuyse)

Groundwater is especially important in the arid PEL073 ReconAfrica license area in Namibia. Because the Omatako River within PEL073 is ephemeral, rural people rely predominantly on shallow groundwater, especially close to the river (Jones, 2010). Groundwater is used for domestic and livestock supplies to villages, rural communities, and farms (Christelis and Struckmeier, 2011). The boreholes and dug wells that supply water are concentrated, as are the people, along the Omatako river valley.

ReconAfrica has started to drill their first exploratory well within the Omatako river valley in January 2021 (Barbee and Neme, 2021) and reports surfaced that the reserve pit where returned drilling fluids and wastewater is being stored, is not lined (Barbee, 2021). This poses a serious contamination risk to the groundwater resources in the Omatako valley. With a shallow groundwater level of less than 30m, and with sandy unconfined aquifers into which contaminants can easily migrate, the groundwater in the Omatako valley is especially vulnerable (Christelis and Struckmeier, 2011). Recharge of the groundwater system occurs mainly via the river systems (Jones, 2010). Once aquifers in arid areas are contaminated, it is nearly impossible to clean up, and this contamination, therefore, poses a legacy contamination risk.

Future exploration that may include drilling in the PEL001 licence area near the Okavango delta in Botswana, also poses a legacy contamination risk to the delta. The Okavango delta does not have an outlet to the sea, and any contamination that enters the delta will therefore accumulate, as confirmed by a continued increase in the salinity of the water in the delta over time (Oromeng et al., 2020).

Both Namibia and Botswana require environmental impact assessments for oil and gas extraction, and public participation as part of the EIAs. There were, however, numerous reports of poor public participation (Esterhuyse, 2020) when ReconAfrica applied for its licenses. ReconAfrica is dismissive of any water impact that may emanate from its activities (Barbee, 2021). The poor management and lax regulation of oil and gas exploration in the Okavango threatens its water resources and should be handled with much more care.

The exploration areas cover a large region of extremely sensitive areas and span across international borders. A strategic environmental assessment should therefore have been performed in addition to the EIAs. A baseline of water resources in the license areas has not been done, nor do proper regulations exist to protect its water resources. The apparent lack of transparency of ReconAfrica in sharing information about its activities (Barbee and Neme, 2021) is also worrying. Without transparency, Botswana and Namibia may not be able to avoid a resource curse, and would not be able to properly manage or monitor the transboundary effects of exploration and extraction activities on shared water resources.

Case study 2: Fracking in South Africa

Unconventional gas extraction using hydraulic fracturing is seen as a way for South Africa to achieve energy security and can assist the country in meeting its socio-economic development agenda (Ndlovu and Inglesi-Lotz, 2019). In 2011, Shell applied for a shale gas extraction license, covering approximately 180 000 km^2, in the central part of the country in an area known as the Karoo (Figure 3-1). The mean annual precipitation in the Karoo ranges from 500 mm in the east to less than 100 mm in the west. The arid Karoo is ecologically sensitive and most of its rivers are ephemeral (Esterhuyse et al., 2016). Groundwater is therefore its most important water source, with most agriculture and towns in the central and western Karoo depending on it (see Figure 3).

The limited water resources and sensitive landscape limits economic and agricultural activities (Walker et al 2018). Agricultural activity, supporting around 100 000 people in the area (Oettle et al; Murcott and Webster 2020), mostly focuses on livestock farming, including dairy farming and wool and meat production, but also includes other activities such as seed crop production. The Karoo people have low employment levels and are poverty-stricken, with a high dependency on social grants (Redelinghuys, 2016). They can not mitigate the impacts of water pollution and water scarcity. Karoo towns also experience ongoing issues with service delivery that fuel social and political unrest. Service delivery protests are strongly linked to water access, which is exacerbated by the limited institutional capacity of the poorly functioning municipalities (Atkinson et al., 2016).

Fracking can potentially disrupt the Karoo's natural ecosystem through the use and pollution of scarce water resources, negatively impacting the health and wellbeing of the people and the natural environment. Because of this, a strategic environmental assessment (SEA) for shale gas development has been done in the Shell permit area (Scholes et al., 2016), Figure 3-1. This SEA highlighted the risk of shale gas development for polluting Karoo groundwater resources, and crucially stated that no additional inland water is available for fracking. Because of this, the Petroleum Agency of South Africa commissioned the development of a regional baseline groundwater monitoring network (GWD GSSA, 2021) to assess the baseline groundwater quality and quantity. South Africa is also developing regulations to protect water resources during fracking (RSA, 2021). These management tools will assist in protecting the scarce Karoo water resources, and no UOG extraction licenses are being granted until these management tools are in place.

Glossary

Biotic homogenization:	Biotic homogenization is defined as the increase in similarity (or decrease in beta-diversity) among ecological communities over time, at the genetic, taxonomic or functional levels.
Coalbed methane:	Natural gas contained in coal beds. Although extraction of coalbed methane was initially undertaken to make mines safer, it is now typically produced from unmineable coal seams.
Coal seam gas:	Coalbed methane is known as coal seam gas in Australia.
Command-and-control regulations:	Command-and-control regulations are by far the most commonly used to minimize damage caused by unconventional oil and gas extraction. They are most often used by countries where regulators are under-capacitated to police self-regulation, such as developing countries.
Conventional oil and gas:	Conventional oil and gas resources are produced from conventional reservoirs. Conventional oil is trapped underneath seals in deep porous geological formations. Gas that occurs in association with this oil, is called

	associated gas. This oil and gas migrated from unconventional reservoirs like shale. Gas that occurs in a porous formation underneath a seal and that is not associated with oil, is called non-associated gas.
Conventional reservoir:	For oil gas reserves, conventional hydrocarbons refer to hydrocarbons that are produced from reservoirs that do not require stimulation to produce the gas. These reservoirs typically have permeabilities larger than 1 milliDarcy. The oil in these reservoirs migrated from source rocks and accumulated in the reservoirs (commonly porous sandstone or carbonate). Conventional reservoirs are capped by impenetrable material (often shale or salt) that keeps the conventional oil in place.
Cradle-to-grave principle:	A lifecycle assessment of the environmental impacts of an industry (Glavič and Lukman 2007)
Darcy:	A unit of permeability. A medium with a permeability of 1 Darcy permits a flow of 1 cm^3/s of a fluid with viscosity 1 cP (1 mPa•s) under a pressure gradient of 1 atm/cm acting across an area of 1 cm^2.
Depressurisation:	Depressurisation is the act of lowering the reservoir pressure below the saturation point (i.e., the critical desorption pressure), which causes gas to desorb from the microporous structure and flow toward the wellbore, where the gas can be produced, processed, and delivered to market. Depressurization can be accomplished by allowing free gas within the naturally occurring or induced fractures in the coal to flow to the surface, or by pumping out any natural fluids occupying the connected cracks and fractures. This fluid can be a combination of formation water and free gas.
Ecosystem engineers	Keystone species that create, modify, maintain or destroy a habitat. Their behavior strongly affects other organisms (e.g., impact on species richness) and landscape heterogeneity.
Ecosystem services	The benefits provided by the natural environment and from healthy ecosystems to humans.
Enhanced oil recovery (conventional oil and gas):	Enhanced recovery can follow primary recovery during conventional oil and gas extraction to maintain pressure and keep up the oil production rate. Enhanced recovery is divided into secondary and tertiary recovery and may use large volumes of water.
Environmental crime:	Any violation of an environmental regulation for which criminal liability may be imposed. Regulations must contain provisions that establish criminal liability for violations. Criminal enforcement of environmental regulations is often used in only the most egregious cases, where the actual or potential damages are excessive or where the violator is a repeat offender. Although criminal enforcement actions are mainly taken to deter future misconduct by the individuals charged, their greater impact may be to deter those who are contemplating similar offenses.
Environmental impact assessment:	The process of evaluating the likely environmental impacts of a proposed oil and gas project or development on a project level, taking into account inter-related socio-economic, cultural and human-health impacts, both beneficial and adverse.
Environmental justice/ injustice:	Environmental justice implies that everyone in society, regardless of their social class, status, background, race, ethnicity or gender must share

	equally in the benefits, risks and negative impacts of developments. Environmental injustice occurs when some people or groups, as a result of their social class, status, background, race, ethnicity or gender, experience most of the harm and risk associated with development, while not receiving a fair share of the benefits.
Flowback (unconventional oil and gas):	Fluid that is returned to the surface after hydraulic fracturing has occurred, but before the well is placed into production. It typically consists of returned fracturing fluids in the first few days following hydraulic fracturing which are progressively replaced by produced water.
Geological formation:	A geological rock body that is distinguishable from other rock bodies and that is useful for geological mapping or description. Formations may be combined into groups or subdivided into members.
Groundwater:	Water that occurs below the surface of the earth, where it occupies all or part of the void spaces in soils or geologic strata.
Hydraulic fracturing:	The act of pumping hydraulic fracturing fluid into a formation to increase its permeability. Hydraulic fracturing has been used in the industry in various forms, for either stimulation of water wells to produce water, or for stimulation of oil and gas wells to produce oil and/or gas. Various technologies can be combined or used separately during hydraulic fracturing. It may involve the use of only water (for water well stimulation) or a combination of any or all of four separate technologies, viz. directional drilling, the use of high volumes of fracturing fluids, the use of slickwater additives and the use of multi-well drilling pads. When all four technologies are combined it is more specifically called “High-volume slickwater long-lateral” (HVSLL) stimulation. Hydraulic fracturing as used in the oil and gas industry, commonly includes the usage of 0.5-2% chemical additives (slickwater additives), large volumes of proppant as well as large volumes of fluid. Base fluids that may be used may include water, liquid petroleum gas or other gases such as nitrogen or carbon dioxide. Synonyms for hydraulic fracturing as used in the oil and gas industry include “slickwater fracking” (“slickwater” in short), “high volume hydraulic fracturing” or just “fracking” or “fraccing” in short.
Hydraulic fracturing fluid:	Fluid used to perform hydraulic fracturing; includes the primary carrier fluid, proppant material, and all applicable additives.
Hydrocarbon:	A naturally occurring organic compound comprising hydrogen and carbon. Hydrocarbons can be as simple as methane [CH_4], but many are highly complex molecules, and can occur as gases, liquids or solids. The molecules can have the shape of chains, branching chains, rings or other structures. Petroleum is a complex mixture of hydrocarbons. The most common hydrocarbons are natural gas, oil and coal.
Injection well:	An injection well is used to place fluid underground into porous geologic formations. These underground formations may range from deep sandstone or limestone, to a shallow soil layer. Injected fluids may include water, wastewater, brine (salt water), or water mixed with chemicals.
Market-based regulations:	Market-based regulations encourage behavior through market signals rather than through explicit directives regarding pollution control levels or

	methods and allow companies to determine the best way to control or minimise pollution (Zhang, 2013).
Peak oil:	The hypothetical point in time when the global production of oil reaches its maximum rate, after which production will gradually decline.
Polluter pays principle:	This principle requires that the polluter pay for the cleanup costs of pollution (Olaniyan 2015).
Primary recovery (conventional oil and gas):	Primary recovery is used in the first stage when natural pressures in the oil reservoir are sufficient to bring oil to the surface. No additional water is needed during this stage of conventional oil extraction.
Produced water:	Natural fluids that are displaced from the geological formation that holds the hydrocarbons, which can contain substances that are found in the formation, and may include dissolved solids (e.g. salt), gases (e.g. methane, ethane), trace metals, naturally occurring radioactive elements (e.g. radium, uranium), and organic compounds. It includes water moving in from adjacent aquifers or formations. In conventional oil formations it also includes water injected in the formation during water and steam flooding.
Regulations:	Environmental regulations are rules to protect public health and the environment from adverse effects by the oil and gas industry. There are three types of regulations: command-and-control, market-based and voluntary.
Reserves (proved):	The quantity of energy sources estimated with reasonable certainty, from the analysis of geologic and engineering data, to be recoverable from well-established or known reservoirs with the existing equipment and under the existing operating conditions
Reservoir (oil or gas):	A subsurface, porous, permeable or naturally fractured rock body in which oil or gas has accumulated. A gas reservoir consists only of gas plus fresh water that condenses from the flow stream reservoir. In a gas condensate reservoir, the hydrocarbons may exist as a gas, but, when brought to the surface, some of the heavier hydrocarbons condense and become a liquid.
Resource curse:	The resource curse (or the paradox of plenty) refers to the failure of many resource-rich countries to benefit fully from their natural resource wealth (such as oil and gas, land and water), and for governments in these countries to respond effectively to public welfare needs. Sharing resources such as land, water, and minerals can create conflict between the extraction companies and the communities. While one might expect to see better development outcomes after countries discover natural resources, resource-rich countries tend to have higher rates of conflict and authoritarianism, and lower rates of economic stability and economic growth, compared to their non-resource-rich neighbors.
Secondary recovery (conventional oil and gas):	Secondary recovery employs water in the form of waterflooding, or gas injection, to displace the oil and drive it to the surface.
Seismicity:	The frequency, intensity, and distribution of earthquakes in a given area.

Shale:	A fine-grained sedimentary rock composed mostly of consolidated clay, silt or mud. Shale is formed from deposits of mud, silt, clay, and organic matter, usually laid down in calm seas or lakes.
Shale gas:	Natural gas that remains tightly trapped in shale and consists chiefly of methane, but with ethane, propane, butane and other organic compounds mixed in. It forms when black shale has been subjected to heat and pressure over millions of years, usually at depths of 1,500 to 4,500 metres below ground level.
Strategic environmental assessment:	Strategic environmental assessments aim to integrate environmental, socio-economic, and human health considerations in a transparent manner into government policies, plans, and programmes at the earliest stage of decision-making, and should be used in conjunction with EIAs.
Subsistence lands	Land areas where indigenous/ local communities hunt, fish, and gather wild-growing fruit and vegetables.
Surface water:	Any body of water above ground, including streams, rivers, lakes, wetlands, reservoirs, and creeks.
Tight sands:	A geological formation consisting of a matrix of typically impermeable, non-porous tight sands.
Tertiary recovery (conventional oil and gas):	Tertiary recovery employs steam or gas to change the makeup of the oil reservoir to enhance the recovery of oil in the reservoir.
Unconventional oil and gas:	Unconventional oil and gas resources are produced from unconventional reservoirs. Unconventional oil and gas include tight oil, oil sands, oil shale, shale gas, tight gas, and coalbed methane.
Unconventional reservoir:	Reservoirs, which require hydraulic fracturing for the extraction of hydrocarbons occurring in these reservoirs, where the permeability is less than 1 milliDarcy.
Voluntary regulations:	Voluntary regulations are usually innovative voluntary actions that oil and gas companies take to improve environmental quality, natural resource utilisation or their environmental performance.
Water stress:	The ratio of annual water withdrawals to renewable water resources of a country.
Waterflooding:	A form of enhanced oil recovery where the energy required to move the oil from the reservoir rock into a producing well is supplied from the surface by means of water injection and the induced pressure from the presence of additional water.

List of relevant web pages:
World Petroleum Assessment. https://certmapper.cr.usgs.gov/data/apps/world-energy/
World Water Stress. https://ourworldindata.org/water-use-stress
Nigerian Oil Spill Monitor https://oilspillmonitor.ng/