ENVIRONMENTAL CONSIDERATIONS IN OFFSHORE FRESHENED GROUNDWATER UTILIZATION

An OFF-SOURCE Report

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Executive Summary

Offshore Freshened Groundwater (OFG) is emerging as a potential solution to growing water scarcity in coastal regions impacted by population growth and climate change. While OFG could reduce pressure on overexploited onshore aquifers and enhance water security, its environmental impacts remain insufficiently understood. This report, developed under the OFF-SOURCE COST Action's Working Group 4, assesses potential risks and opportunities through a stakeholder survey and a review of analogous offshore industries.

The stakeholder survey revealed conditional support for OFG: 69% favored its use if both environmentally sustainable and cost-effective. Identified risks span drilling, pumping, treatment, and infrastructure phases, including habitat disturbance, aquifer contamination, saline intrusion, greenhouse gas emissions, brine disposal, subsidence, and disruption of marine ecosystems. Comparisons with offshore oil, wind, geothermal, desalination, and deep-sea mining highlight shared concerns such as habitat loss, sediment disturbance, noise pollution, and ecological uncertainty.

Nevertheless, potential benefits exist if OFG is managed responsibly, including alleviating stress on freshwater resources, creating artificial reef habitats, reducing brine waste, and providing a lower-carbon alternative to traditional desalination. The study emphasizes the urgent need for interdisciplinary collaboration, regulatory clarity, and continued research to balance water security gains against environmental and societal risks.

AUTHORS

Elizabeth Quiroga Jordan
Nataša Čereković
Hamid Abdalla Hamid

TABLE OF CONTENTS

01 | Introduction

Water scarcity is a growing global concern, particularly in coastal regions facing pressures from population growth, pollution, climate change, and political conflicts (IPCC, 2022). Offshore Freshened Groundwater (OFG)—water stored in sub-seafloor sediments with lower salinity than seawater—is being explored as an alternative freshwater source to help mitigate these challenges (Micallef et al., 2020). OFG has potential to buffer drought effects and reduce reliance on stressed coastal aquifers.

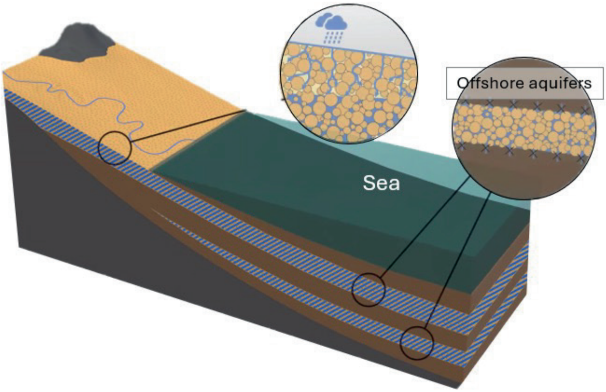


Figure 1. Schematic of offshore aquifers that were likely emplaced during past periods of sea level lowstand. From OFF-SOURCE 2025. Graphic design: Lina Jakaité.

However, the environmental impacts of OFG utilization remain poorly understood. Potential risks include reduced availability of onshore groundwater (Yu & Michael, 2019a), loss or contamination of submarine groundwater discharge affecting ecosystems (Varma & Michael, 2012; Amato et al., 2016), seawater intrusion (Houben & Post, 2017), and subsidence (Yu & Michael, 2019b). Additional concerns involve brine disposal, habitat disturbance, drilling-related pollution, and cross-contamination (Ghaffour et al., 2013; Bakken et al., 2012). Legal uncertainties further complicate OFG development, particularly in areas shared between states or beyond national jurisdiction (Martin-Nagle, 2020).

This report summarizes the key findings from a study designed to identify and assess the environmental and legal implications of OFG extraction. Through a stakeholder survey and literature review, it seeks to inform best practices and promote cross-sector collaboration to guide future research and responsible OFG utilization.

The authors recognize the limited knowledge on this topic and present this work as a first attempt to map the potential environmental impacts. The report primarily examines the environmental aspects of OFG utilization through two complementary approaches: (1) a survey in which key stakeholders provided insights into the potential impacts of OFG extraction, and (2) a literature review focusing on environmental impacts from offshore resource exploration that may be applicable to OFG.

02 | Environmental impacts mapped via a stakeholder survey

As part of the activities of OFF-SOURCE COST Action's working group 4, a detailed stakeholder questionnaire was conducted to identify anticipated environmental impacts related to OFG pumping, transportation, treatment, and distribution. More details about this survey can be found in Section 5.

Acceptance of OFG as a viable water source was largely conditional, as illustrated in Figure 2. A significant majority (69%) supported its use if it proved both cost-effective and environmentally sustainable. Additionally, 17.9% would accept it if it were available in their region, while 9.3% favoured if it was the lowest-cost solution, and 3.6% prioritized the lowest environmental impact. Only 1.2% of respondents rejected the idea outright.

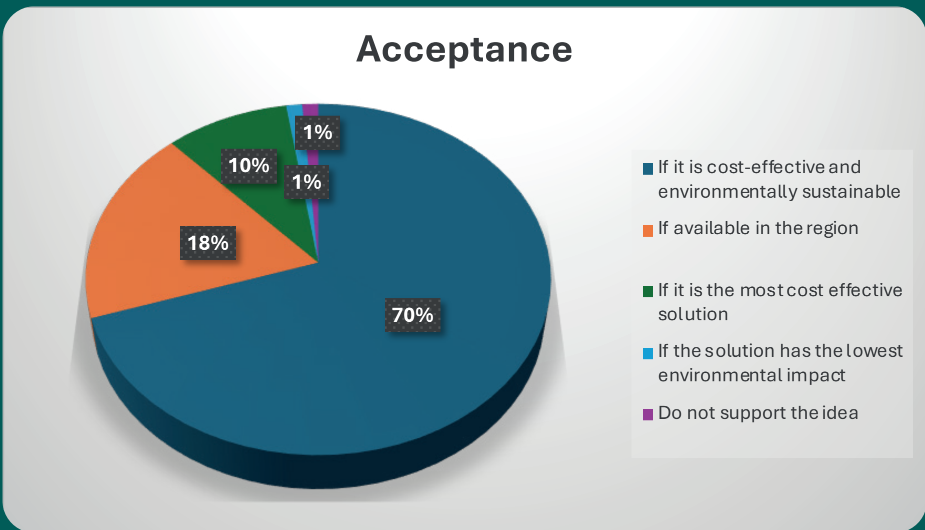


Figure 2. Acceptance of Offshore Freshened Groundwater (OFG) utilization among surveyed participants.

Risks associated to OFG extraction

This section focuses on the risks associated to each stage of OFG extraction, mapped by the survey respondents. Activities for OFG utilization are grouped into four main stages and risks associated to each activity were mapped as follows:

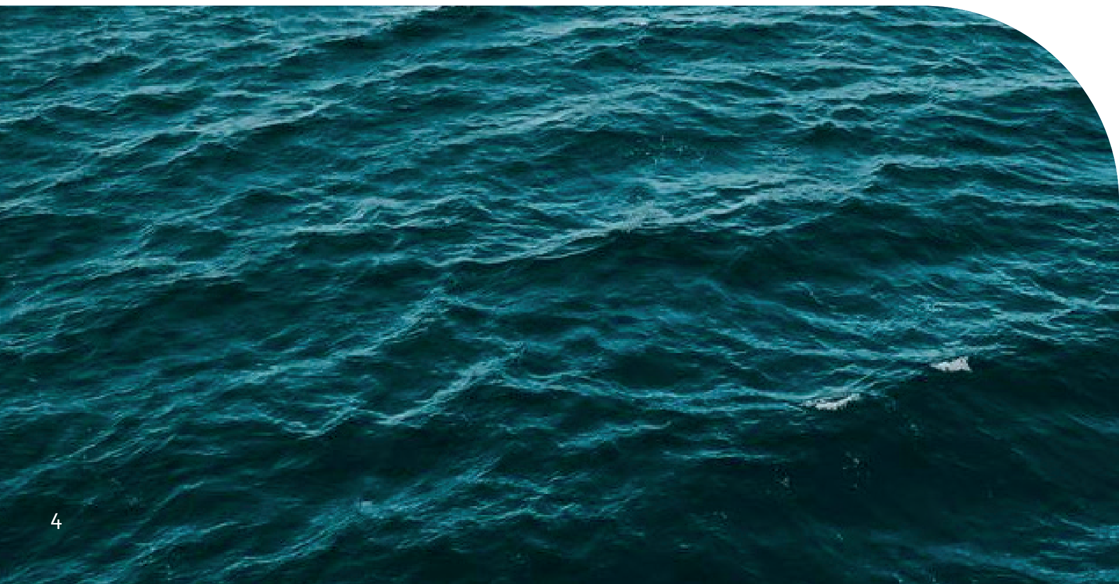
A) Drilling and completion operations

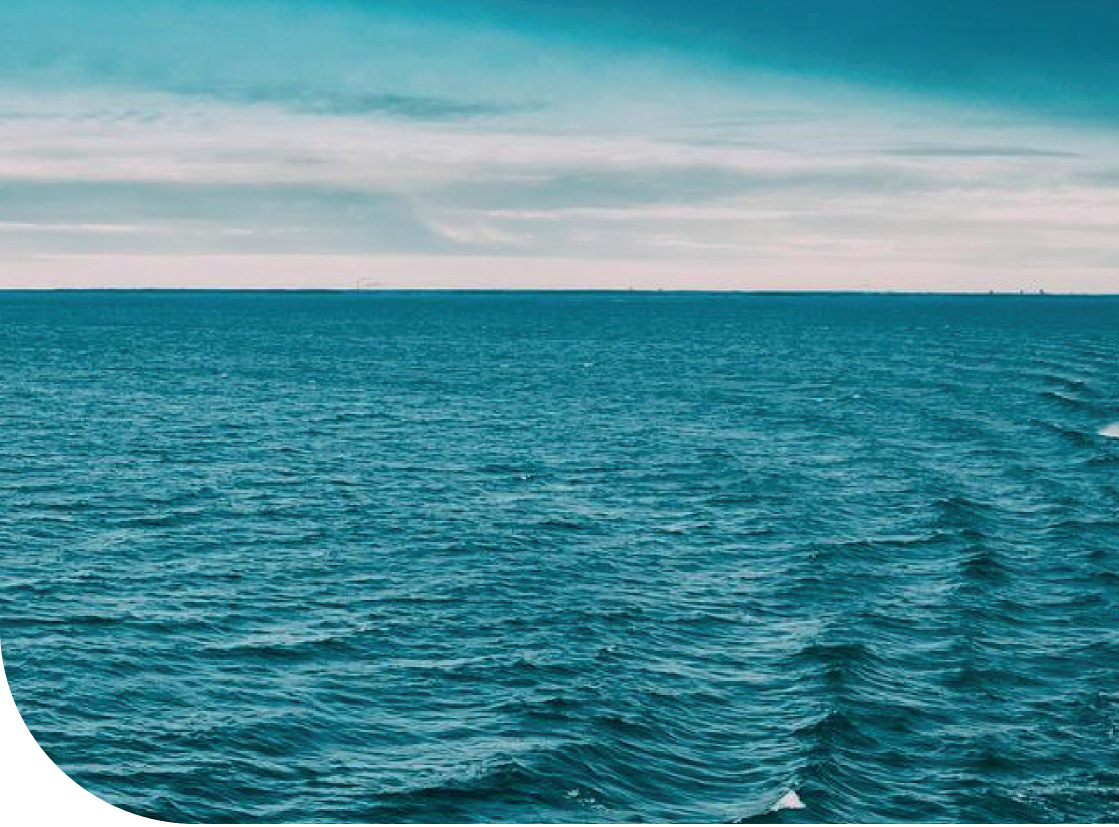
- Marine ecosystem disturbance: Drilling disrupts the seafloor, causing sediment displacement, which can smother benthic habitats and reduce light penetration, affecting marine flora and fauna. The noise and vibrations from drilling may also interfere with the behaviours of marine species.

- Cross-contamination of aquifers: Drilling through multiple geological layers increases the risk of cross-contamination, where saline water infiltrates freshwater aquifers. If well integrity is not properly maintained, this can permanently degrade OFG resources and impact water quality.

- Greenhouse gas emissions from equipment and operations: Drilling and completion activities rely on heavy machinery, which consumes large amounts of fuel, contributing to CO_2 and other greenhouse gas emissions. These emissions exacerbate climate change and contribute to ocean acidification, which can further affect marine ecosystems.

- Habitat destruction due to infrastructure placement: The placement of drilling rigs and related infrastructure can damage coral reefs, seagrass beds, and other critical marine ecosystems. This destruction can reduce biodiversity, disrupt breeding grounds, and contribute to coastal erosion.





B) Pumping, extraction, and transportation

- Risk of saline intrusion: Over-extraction can lower the pressure in offshore aquifers, allowing seawater to seep into freshwater zones. This process can permanently compromise groundwater quality, making it unsuitable for consumption and agricultural use.

- Pipeline leaks and contamination: This is a risk observed in the oil industry as hydrocarbons inside the pipelines can leak and contaminate water. However, in this case, pipelines transport fresh-brackish water, which present negligible contamination risk..

- Noise and light pollution affecting marine life: Pumping and transportation activities generate constant noise, which can disrupt marine species' communication, feeding, and reproductive behaviours. Additionally, artificial lighting from offshore operations can disorient marine organisms, altering migration and breeding patterns.

- Seafloor subsidence: The removal of large volumes of water from offshore aquifers may lead to seabed subsidence, potentially altering underwater topography and coastal stability. This can increase vulnerability to erosion and lead to habitat loss for species dependent on stable seabed conditions.

C) Water treatment and desalination

OFG may require additional processes to make the water potable. These processes can include desalination or advanced water treatment to remove dissolved minerals and/or salts.

- Brine disposal affecting marine salinity levels: The desalination process generates brine, a highly saline byproduct that, if discharged directly into the ocean, can create hypersaline zones. These zones can alter local marine ecosystems, leading to reduced oxygen levels and threatening marine species adapted to stable salinity conditions.

- High energy consumption contributes to carbon emissions: Water treatment and desalination are energy-intensive processes, particularly if reverse osmosis or thermal desalination techniques are used. If powered by fossil fuels, these operations significantly contribute to greenhouse gas emissions, exacerbating climate change and increasing the carbon footprint of OFG utilization.

- Chemical use leading to potential contamination: The treatment process often involves the use of chemicals such as coagulants, disinfectants, and anti-scaling agents. If not properly managed, residual chemicals can be released into marine and coastal environments, leading to toxic effects on aquatic life and bioaccumulation in the food chain.

D) Infrastructure and long-term impacts

- Abandoned platforms causing pollution or serving as artificial reefs: Decommissioned offshore structures can either contribute to pollution through rusting materials and leaks or, if properly managed, provide habitats for marine life, serving as artificial reefs (https://www.bbc.com/future/article/20210126-the-richest-human-made-marine-habitats-in-the-world). The effectiveness of artificial reefs depends on proper site selection and structural integrity.

- Seabed pressure dynamics affecting coastal hydrology: Large-scale OFG extraction can alter subsurface pressure balances, affecting groundwater flow patterns both offshore and on land. These changes could impact coastal aquifers, potentially leading to unexpected shifts in freshwater availability for coastal communities.

- Risk of ecosystem imbalance from groundwater modifications: Modifying offshore groundwater flows can have cascading ecological effects, potentially disrupting natural submarine groundwater discharge (SGD) processes that provide nutrients to marine ecosystems. Changes in these flows can influence biological productivity, species composition, and overall ecosystem stability.

Potential Positive Environmental Impacts

While much of the discussion around OFG extraction has focused on potential risks, some survey respondents highlighted possible environmental benefits if extraction is conducted sustainably. The following are key positive environmental impacts identified in the survey:

- Reduced pressure on surface water resources: Utilizing OFG as an alternative freshwater source could alleviate stress on overexploited rivers, lakes, and onshore aquifers, contributing to better freshwater management.

- Potential for Artificial Reefs: If decommissioned infrastructure is managed properly, abandoned rigs and platforms could serve as artificial reefs, promoting marine biodiversity.

- Low carbon footprint compared to some desalination methods: OFG extraction, if powered by renewable energy, may present a lower carbon footprint compared to energy-intensive desalination processes.

- Enhanced water security in coastal regions: Sustainable extraction of OFG could provide a new, reliable source of freshwater for drought-prone coastal areas, reducing dependence on traditional water sources.

03 | Anticipating Environmental Impacts of OFG Through Comparisons with Related Offshore Industries

To anticipate and evaluate the potential environmental impacts associated with Offshore Freshened Groundwater (OFG) utilization, a review of analogous offshore and marine industrial activities provides a valuable baseline. This synthesis draws on environmental assessments across five key sectors—offshore oil and gas extraction, offshore wind farms, offshore geothermal energy, seawater desalination, and deep-sea mining—to identify relevant environmental risks.

Habitat Degradation

Across all reviewed sectors, habitat degradation is a recurring concern. Offshore oil and gas infrastructure, such as drilling platforms and pipelines, disturbs benthic environments and leads to biodiversity loss (Olaleye et al., 2024). Deep-sea mining irreversibly disrupts polymetallic nodule fields, which are critical to deep-sea biodiversity (WWF, 2021; Harvard International Review, 2021). Similarly, geothermal energy development may affect hydrothermal vent ecosystems and seamounts, which are ecologically significant and slow to recover (Pedamallu et al., 2018).

Sediment Disturbance and Turbidity

Construction activities for wind farms and geothermal projects increase sedimentation and turbidity, negatively impacting coral recruitment, fish feeding, and benthic communities (Rahman & Kumar, 2024; Pedamallu et al., 2018). Deep-sea mining produces sediment plumes that smother organisms and reduce light penetration (Jones et al., 2017).

Changes in Salinity and Nutrient Gradients

Produced water discharge from oil and gas operations alters marine salinity and nutrient composition (Olaleye et al., 2024), while brine from desalination plants creates hyper-saline layers that accumulate on the seafloor, disrupting marine life (Sola et al., 2019; Baalousha, 2006). OFG extraction may produce similar risks if discharge alters ambient salinity or upsets nutrient dynamics.

Risk of Chemical Pollution

Chemical contamination is widespread: oil and gas operations release hydrocarbons and heavy metals (Olaleye et al., 2024); desalination plants discharge biocides and cleaning agents (Sola et al., 2019); and wind turbine anti-corrosion coatings may leach toxins such as bisphenol A and zinc (Alawady et al., 2024). These pollutants can have long-term ecological consequences, especially in poorly flushed environments.

Noise Pollution

All sectors generate substantial underwater noise, from seismic surveys and drilling (oil and gas) to pile driving (wind farms), and geothermal exploration (Pedamallu et al., 2018). Noise pollution interferes with communication, navigation, and reproductive behaviors of marine fauna, including cetaceans and fish (Olaleye et al., 2024; Rahman & Kumar, 2024).

Electromagnetic Field (EMF) Effects

EMFs produced by subsea power and data cables—used in wind, geothermal, and OFG projects—can disrupt the navigation and foraging behavior of species such as sharks and rays (Rahman & Kumar, 2024; Pedamallu et al., 2018). Long-term EMF exposure risks remain under-researched but are increasingly recognized.

Impact on Fisheries and Local Livelihoods

Oil spills, deep-sea sediment disturbance, and reduced water quality from brine discharge may impact fisheries and the livelihoods of coastal communities (WWF, 2021; Sola et al., 2019). These impacts underscore the socioeconomic dimensions of offshore environmental management.

Limited Ecological Understanding

Deep-sea ecosystems, hydrothermal vents, and groundwater-seawater interactions remain poorly understood (WWF, 2018; Pedamallu et al., 2018). This knowledge gap hampers the ability to predict and mitigate impacts from OFG or any new offshore industrial activity with precision.

Changes in Discharge Patterns

Desalination and OFG operations can alter discharge regimes—thermal, saline, and chemical—which affect water column stratification, nutrient cycling, and habitat suitability (Baalousha, 2006; Alawady et al., 2024). These changes may lead to ecosystem shifts at both local and regional scales.

Unique Species at Risk

Hydrothermal vents (geothermal) and deep-sea mining zones host endemic species adapted to specific chemical and thermal conditions. These organisms face extinction risks from disturbance due to narrow ecological niches and low reproductive rates (Pedamallu et al., 2018; WWF, 2018).

Energy Use and Carbon Footprint

All activities—particularly oil and gas extraction and desalination—are energy-intensive and contribute to greenhouse gas emissions. Offshore oil operations, especially in the Arctic, accelerate climate-related changes in sensitive ecosystems (Olaleye et al., 2024; Baalousha, 2006).

04 | Summarizing key findings

The table below summarizes potential environmental impacts relevant to Offshore Freshened Groundwater utilization. The results demonstrate that most potential impacts were successfully identified in the survey, except for electromagnetic field effects that OFG installations could have on marine organisms. Conversely, the survey effectively mapped additional environmental impacts specifically related to hydrogeology, including saline intrusion, aquifer depletion, and subsidence. This highlights the importance of involving domain-specific experts (in this case hydrogeologists), in environmental impact assessments. Additionally, the survey highlighted broader concerns, such as limited ecological understanding of OFG systems and potential changes in discharge patterns that may affect marine and coastal environments.

The successful identification of a wide range of potential impacts, and the discovery of new hydrogeological concerns, underscores the critical need for interdisciplinary expert collaboration in environmental impact assessments for OFG projects.

Table 1. Anticipated potential environmental impacts of OFG utilization

POTENTIAL ENVIRONMENTAL IMPACT	MAPPED WITH THE SURVEY	ANTICIPATED AFTER REVIEWING SIMILAR OFFSHORE ACTIVITIES
Habitat degradation	Yes	Yes
Sediment disturbance and turbidity	Yes	Yes
Changes in salinity and nutrient gradients	Yes	Yes
Risk of chemical pollution	Yes	Yes
Noise pollution	Yes	Yes
Electromagnetic field effects	No	Yes
Impact on fisheries and local livelihoods	Yes	Yes
Limited ecological understanding	Yes	Yes
Changes in discharge patterns	Yes	Yes
Unique species at risk	Yes	Yes
Aquifer depletion	Yes	No
Saline water intrusion	Yes	No
Subsidence	Yes	No
Energy use and carbon footprint	Yes	Yes

05 | Details on the stakeholder survey

As part of the activities of OFF-SOURCE COST Action's working group 4, a detailed stakeholder questionnaire was conducted to identify anticipated environmental impacts related to OFG pumping, transportation, treatment, and distribution. Stakeholders were categorized into five groups, and corresponding OFF-SOURCE Action members were assigned to engage with each group. Their primary responsibility was to establish contact with stakeholders from COST countries; however, contributions from stakeholders in non-COST countries were also welcomed if deemed relevant to the research.
The stakeholder subgroups were defined as follows:

Subgroup 1: Civil society (e.g., NGOs)
Subgroup 2: Government (e.g., Ministries)
Subgroup 3: Authorities (e.g., local authorities, TPDC, international authorities such as maritime organizations, IMO, UN agencies, country-level and regional-level authorities)
Subgroup 4: Private sector and other relevant actors
Subgroup 5: Research institutions, academia, and universities

Recognizing that some stakeholder groups might be more accessible than others, the minimum number of required engagements varied across categories. Nevertheless, efforts were made to ensure that at least the minimum number of contacts specified for each group was achieved.

The questionnaire was distributed across all subgroups, resulting in a total engagement of 84 participants: 7 from NGOs, 16 from Subgroups Government Agencies and Authorities, 14 from Private Sector, 49 from Research Institutions and Academia, and 3 categorized as 'Other.' Some participants had experience in multiple subgroups, therefore, the total number of responses exceeded the number of participants, resulting in 89 responses in this distribution, summarized in Figure 3.

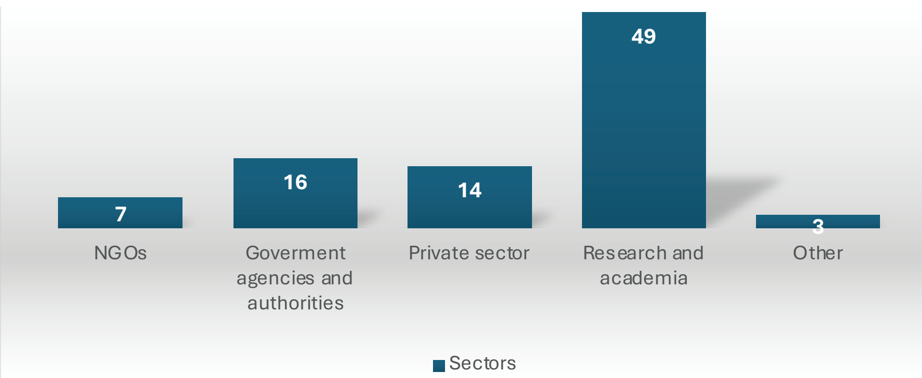


Figure 3. Stakeholders' distribution. Note: Participants were allowed to identify with more than one stakeholder group, so totals exceed the number of individual respondents.

The majority of respondents (43.9%) had more than 20 years of experience in their field, 33.3% had between 10 and 20 years, 17.5% had between 5 and 10 years, and 5.3% had less than 5 years of experience. Experience in related fields was distributed as follows: 39.3% had experience in upstream activities, 10.7% in water distribution, 7.1% in water treatment, 7.1% in pumping, extraction, and transportation, 4.8% in drilling and completion, and 2.4% in planning offshore industrial activities. Additionally, 28.6% reported no experience in the listed technical areas but expressed a general interest in contributing to mapping environmental impacts.

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