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Potential groundwater contamination from oil drilling in the Okavango

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ABSTRACT

Canadian oil and gas company, Reconnaissance Energy Africa (ReconAfrica), plans to exploit potential oil reserves in the Cubango Okavango River Basin (CORB) in Namibia and Botswana, where little is known about the local groundwater systems and how contamination and its effects could impact the region. Using borehole data from target oil and gas areas, we calculated hydraulic gradients, flow direction, and flow velocity to map potential groundwater contamination effects from oil and gas drilling in the region. We also plotted the major geological structures, calculated flowpaths, and estimated travel times for contaminated groundwater that may travel along these preferential flowpaths from the drill sites to the Okavango River and Delta. Results indicate that contaminated groundwater from the oil lease areas could take 3–23.5 years to reach the Okavango River system via the shallow sandy aquifer, but in a worst-case scenario, contamination could reach the Delta within four days via structures associated with dykes and faults that serve as primary flowpaths. Such contamination could adversely affect human health and the region's ecosystems and biodiversity. We recommend prohibiting oil exploration and production activities within the CORB until future studies can determine the impacts of hydrocarbon extraction with greater certainty.

1. Introduction

Oil and gas exploration and production in the Okavango region had long been dismissed as economically unviable (Hiller, 1996) until the announcement that Canadian oil company ReconAfrica obtained licenses for over 35,000 km^2 of land within the Cubango Okavango River Basin (CORB) in Namibia and Botswana. ReconAfrica claims that their transfrontier lease areas could hold up to 31 billion barrels of oil equivalent (ReconAfrica and Quester Advisors, 2021) and that oil production will spur economic growth in the largely impoverished region (ReconAfrica Q2, 2022). These lease areas are, however, located along the borders of the Cubango River and Okavango Delta (Fig. 1) in Namibia and Botswana, where oil drilling could have severe environmental impacts.

As such, the most significant concern for allowing exploration and production of oil in the region is whether contamination from drill sites in the lease area could spread to the Okavango River Basin through surface water and groundwater contamination (Esterhuyse, 2020). We furthermore have a poor understanding of how groundwater contamination from oil exploration and production affects wetland ecosystems (Fetter et al., 2017), and there is a poor understanding of regional groundwater flows in shallow and deep-water aquifers in transfrontier areas across the CORB (Jones, 2010).

Given the transfrontier nature of oil exploration and production in the oil and gas target areas in Namibia and Botswana, international governance and agreements over groundwater play an increasingly important role. In 1995, the governments of Angola, Botswana, and Namibia signed an agreement to form the Permanent Okavango River Basin Water Commission (Pinheiro et al., 2003). The agreement stipulates joint monitoring and planning of projects that might affect the water resources of any of the three states before any development action is taken (Ramberg, 2018). With the potential for groundwater contamination from drill sites crossing international boundaries between Botswana and Namibia, the OKACOM council decided to permit prospecting activities on the condition that the respective Botswana and Namibian ministries oversee all the prospecting activities. The OKACOM agreement requires all regional stakeholders to be consulted, for member states to prepare and submit relevant information to other member states, and for strict Environmental Impact Assessment (EIA) legislation and guidelines to be followed (OKACOM, 2021).

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The Environmental Impact Assessment that the Namibian government authorised in March 2021 claims that there was not enough available data to assess groundwater depth and flow accurately. According to the EIA, data on borehole water rest levels was only available for 35% of boreholes, making an accurate flow model of groundwater impossible. As such, the EIA indicated that groundwater contamination would be largely inconsequential to the Okavango River basin (ReconAfrica Namibian EIA, 2021). However, potential groundwater contamination that may travel across international boundaries would violate the OKACOM agreement directives (OKACOM, 2021).

Our study, therefore, uses publicly accessible borehole data from the Kavango region and Ngamiland district available through the Namibian Ministry of Agriculture, Water, and Land Reform and the Botswana Department of Water Utilities. Geological structure data was obtained from Namibia's Geological Survey and the Botswana Geoscience Information Centre. This study analysed the available data to determine whether contamination from oil drilling sites in the lease area could reach the Okavango River system. More definitive groundwater studies that are based on site-specific data are needed to monitor and manage any contamination that may arise from oil and gas extraction activities.

2. Background

2.1. Oil and gas effects on local and regional systems

Oil and gas extraction generates several waste streams, which are commonly stored at waste storage reservoirs. The reservoirs store flowback, produced water, spent drilling fluids, and used drilling muds and cuttings. Wastewater from these wastewater storage reservoirs and solid waste sites can contaminate both local surface water and groundwater resources (Wójcik and Kostowski, 2020). The wastewater from waste storage facilities may seep directly into groundwater resources, and if geological structures such as faults or fracture zones are present near the waste storage facilities, groundwater contamination may be exacerbated. Faults and fracture zones can act as preferential pathways that may significantly increase the migration of potential groundwater contamination (Loveless et al., 2019).

In seismically active regions, groundwater contamination via geological structures may be even more significant. Wastewater disposal in underground injection wells can also cause seismicity and has significantly increased induced seismicity in the United States, the United Kingdom, Canada, and China, in some cases causing earthquakes as large as magnitude 5.7 (Schultz et al., 2020).

Apart from possibly contaminating surface water and groundwater resources during oil and gas extraction, wetlands can also be affected. Water exchange between surface water and groundwater resources is common in wetland ecosystems, and contamination between these water bodies is highly likely (Winter, 1999). The impacts of wastewater contamination from oil drilling on wetland ecosystems are well-documented. In 2014, wastewater contamination from unconventional oil extraction spilled into the Bear Den Bay wetland ecosystem close to Lake Sakakawea in North Dakota. The effects of the contamination were immediate and devastating to the local ecosystem (Konkel, 2016). In the Niger Delta both surface and groundwater contamination from hydrocarbon extraction has resulted in irreparable damage to ecosystem health to the extent of ecosystem collapse, and this in turn has severely impacted human health throughout the region (Ite et al., 2018; Nnoli et al., 2021; Onyena and Sam, 2020). Various studies have shown significant chemical pollution within groundwater sources as a result of oil production throughout the Niger Delta region (Raimi et al., 2022; Giadom and Tse, 2014). This contamination, which contained hydrocarbon pollutant carcinogens at levels 14,000 times higher than the Nigerian standard for safe drinking water, seeped into drinking water wells and destroyed thousands of square kilometres of mangroves (Lindén and Pålsson, 2013).

Oil and gas well casing failure and leakage can also contaminate aquifers (Ingraffea et al., 2014) and may pose long-term groundwater contamination legacy issues. These legacy impacts are not easy to fix and

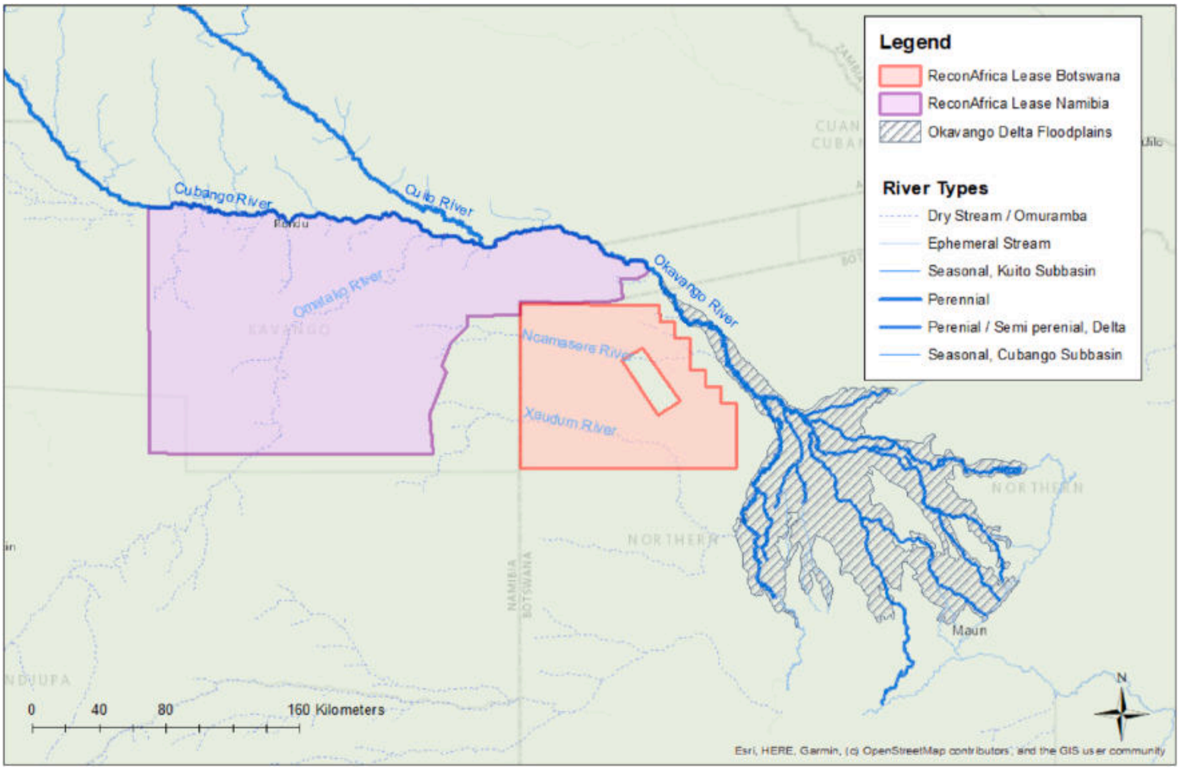

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Fig. 1. ReconAfrica lease areas in Botswana, highlighted in red, and Namibia, highlighted in purple, in proximity to the Okavango River System. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

can span over multiple generations. According to Davies et al. (2014), between 1.9% and 75% of wells from different oil and gas extraction areas worldwide, have 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). Despite the importance of monitoring decommissioned oil and gas wells, these legacy issues are often overlooked during oil and gas extraction planning.

It is also important to point out that the impacts of oil and gas are cumulative within natural environments and do not only occur locally but rather that the effects are noticeable on a regional scale (Esterhuyse et al., 2016).

2.2. The Cubango Okavango river basin

The CORB is one of the largest river systems in Southern Africa with headwaters originating in Angola forming rivers that terminate in an inland delta in the Kalahari Desert. The river system is primarily charged by rainfall in the Angolan highlands which feeds the Cubango and Cuito rivers which converge along the Namibian border into the Kavango River. This river veers south into Botswana where it spreads into an alluvial fan in the Kalahari Desert and forms the Okavango Delta, the largest inland delta on earth. The Okavango Delta is a UNESCO World Heritage and a Ramsar site of global importance and provides an ecosystem that is home to 130 species of mammals, 482 species of birds, and over 1000 species of plants (UNESCO, 2014).

The Omatako River in Namibia flows northeast to enter the Cubango River at the border between Angola and Namibia (FAO 2021). The Omatako is topographically linked to the Okavango River. The river is ephemeral due to the low mean annual rainfall (less than 400 mm/year in the headwaters) (Beuster et al., 2010). Several studies claim that ephemeral flows from the Omatako River do not reach the Okavango River basin or the Delta and that there is no evidence of significant groundwater flows from the Omatako basin toward the Okavango River system (Jones, 2010; Steudel et al., 2013).

However, the Omatako River has episodic flows during high rainfall events (SLR 2019; Arkert 2021) claims that these significant episodic rainfall events, which are increasing due to human-induced climate change, could lead to contaminated surface water flowing into both the Omatako River and the Okavango River System. The FAO (2014) confirms this by stating that groundwater in the Okavango Basin can contribute baseflow to the Cubango River. The Ncamasere and Xaudum Rivers in Botswana (Fig. 1) are both also ephemeral, much like the Omatako River, but water from these rivers does flow into the Okavango River system during episodic rainfall events (Mapani, 2012).

The endorheic Okavango Delta is the terminal sink of the CORB (Milzow et al., 2009; King and Chonguiça, 2016;) and has little or no outflow. The Delta is fed by both base flow from the Okavango River and seasonal floods ((McCarthy and Ellery, 1998); Gondwe et al., 2021). Contaminants that enter the Okavango River system could therefore reach the Delta, where they will be impossible to remove (Arkert, 2021). The hydrological impacts of a changed solute balance within the Okavango Delta terminal sink would significantly impact the ecosystem (Oromeng et al., 2021). Oromeng et al. (2021) hypothesise that groundwater provides a high solute influx to the river system during a hydrological recession.

Little information is available regarding the hydrogeological formations within the CORB, particularly the groundwater occurrences in the region along the lower Cubango and Cuito (Jones, 2010). Mapped geological structure data in the Namibian lease area of ReconAfrica, is also minimal, as confirmed by the Namibian geological survey. Previous groundwater studies were localised and specialised, including studies of trace metals in the Okavango Delta (Dauteuil et al., 2021), groundwater fluctuations in the Delta (Bauer et al., 2004), and coupled surface-groundwater modelling of the Delta (Bauer et al., 2006).

Two aquifer systems underlie the Omatako subbasin and the Okavango subbasin areas - the shallow Kalahari aquifer system and the deeper fractured bedrock aquifers (Christelis and Struckmeier, 2011; Mapani, 2012). The region's geology suggests that groundwater flow occurs through the Kalahari sediments in the shallow aquifer system. In contrast, salinity studies of aquifers deeper than 100 m indicate that the deep aquifer system is static (Jones, 2010).

Groundwater systems in the Okavango support the surrounding wetland ecosystems through surface water-groundwater (SW-GW) interactions (Milzow et al., 2009; Wolski and Savenije, 2006). As wet and dry periods alternate across the floodplains, there is evidence that groundwater is recharged during annual flooding and also that groundwater baseflows contribute to surface water (Wolski and Savenije, 2006). The accepted theory is that the primary interaction between SW-GW occurs when flood water advances into the Okavango Delta so that surface water infiltrates through the soil and the groundwater rises to the surface, making flooding across the plains possible (Milzow et al., 2009).

Groundwater contamination could theoretically enter the Okavango Delta terminal sink along the western periphery during drier months and droughts, Milzow et al. (2009) found that SW-GW interaction occurs at the western margin of the Okavango Delta, where the isotopic composition of the samples indicated direct mixing with regional groundwater. Contamination that enters the western area of the Okavango could move directly into surface water, contaminating groundwater via the SW-GW interactions, which would affect ecosystems throughout the region (Bauer et al., 2004). Groundwater is not only the primary hydrological source for inland island vegetation in the Okavango but also acts as a significant buffer for the overall chemistry of the river by modulating and controlling solutes in the river system (Oromeng et al., 2021).

Within the ReconAfrica lease areas, both conventional and unconventional oil and gas could be extracted in the target oil and gas areas if proven to be economically viable (Sproule Report, 2020; Esterhuyse, 2020; Totten, 2021 Arkert, 2021). Groundwater contamination is the most common environmental threat from conventional and unconventional gas extraction in this region. The water tables of the shallow aquifers in the target oil and gas areas in Botswana and Namibia are in some areas as little as 2 m deep (Christelis and Struckmeier, 2011; Wolski and Savenije, 2006). These shallow water tables can exacerbate localised groundwater pollution in these areas. Groundwater is often the sole water source and is critical to the health and livelihoods of the communities in these regions (Mapani, 2012; Arkert, 2021). Hydrocarbon exploration and extraction has been identified as a relevant threat to groundwater systems (Jia et al., 2019), and contamination of the shallow aquifer system in the ReconAfrica lease areas by unconventional oil and gas (UOG) extraction would likely disrupt and considerably impact the lives of communities in the area (Arkert, 2021).

2.3. The Okavango graben

The Okavango Graben (Fig. 2) was generally interpreted as a young rift zone segment of the East African Rift System (EARS), termed the South-Western branch (Du Toit, 1927; Scholz et al., 1976). However, recent research suggests a pull-apart or transtensional strike-slip basin might be more suitable, with the graben forming part of the South-Western Extension Area (Yu et al., 2015; Pastier et al., 2017).

The area is tectonically active, as made evident by the recorded history of earthquakes illustrated in Fig. 2. Lubrication of the faults by the influx of groundwater and water from the Okavango River could result in more frequent, lower-magnitude earthquakes (Sibson, 2000; Bufford et al., 2012; Pastier et al., 2017). Earthquake events can result in renewed movement on existing faults or the creation of new fractures and/or faults, which could result in pathways connecting contamination sources with receptors via groundwater movement.

Structures can also act as a pathway between petroleum exploration wells and the near-surface (Pietersen et al., 2021). The integrity of oil and gas wells has been a significant problem worldwide (Jackson, 2014;

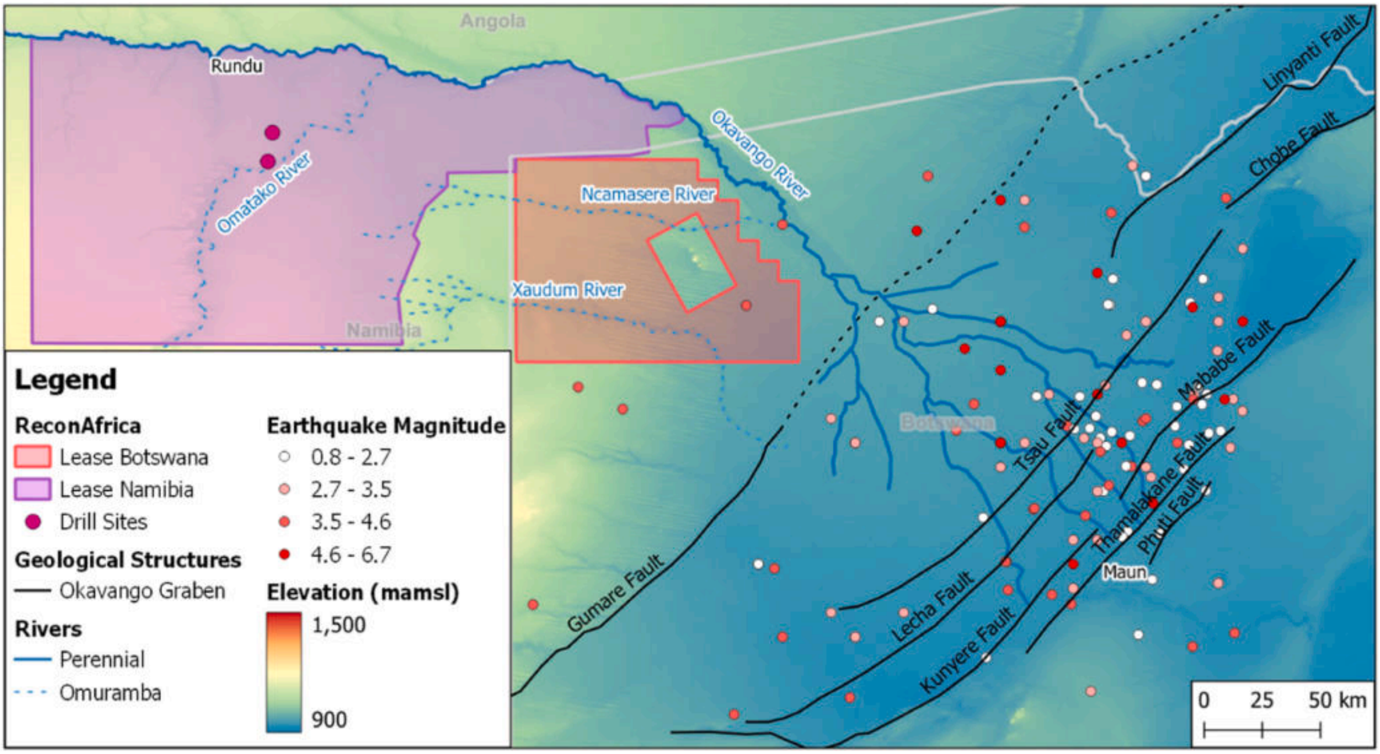

Fig. 2. Map of the Okavango region illustrating the main faults of the Okavango Graben as well as historic earthquake magnitudes. The ReconAfrica Botswana lease is shown in red and the ReconAfrica Namibian lease is in purple. The ReconAfrica drill sites are indicated with purple points. Graben faults were modified after Kinabo et al. (2007). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

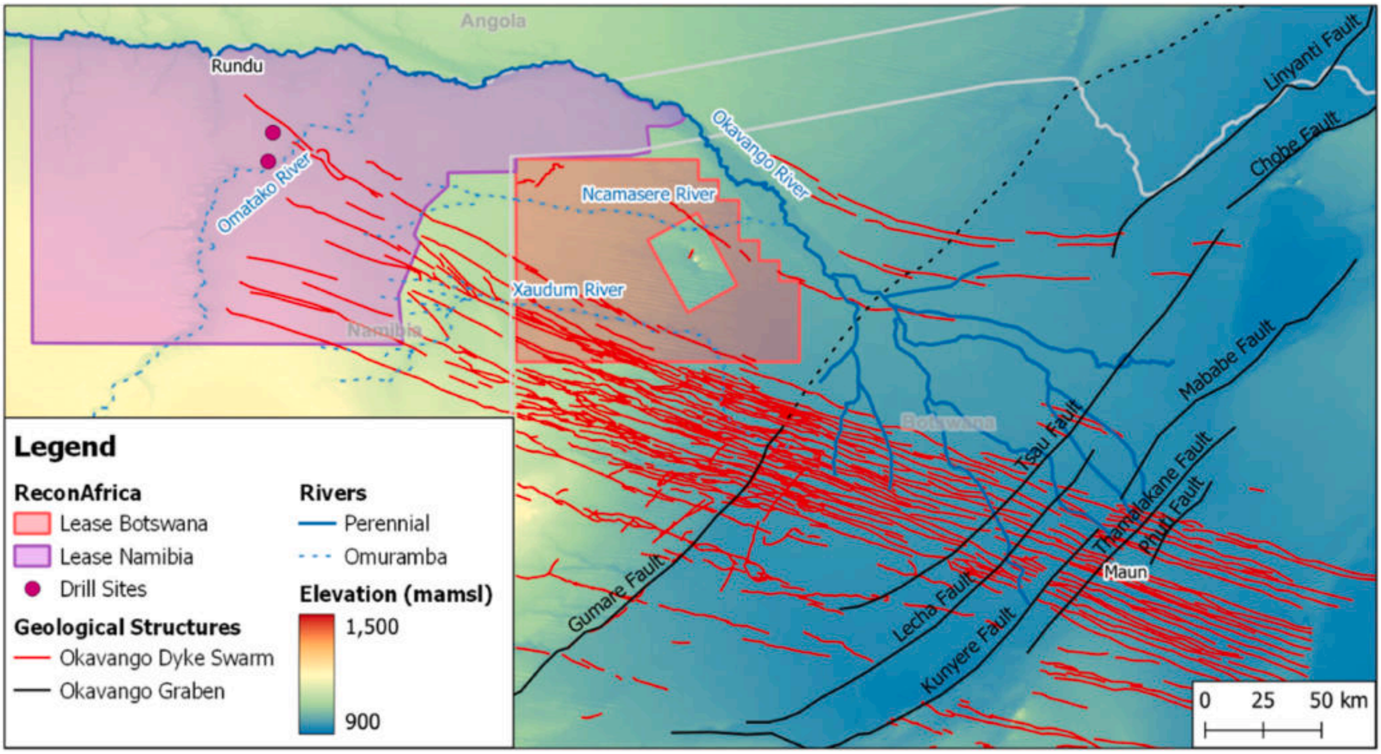

Fig. 3. Map of the Okavango region illustrating the main faults of the Okavango Graben and the dolerite dykes of the Okavango Dyke Swarm. The ReconAfrica Botswana lease is shown in red and the ReconAfrica Namibian lease is in purple. The ReconAfrica drill sites are indicated with purple points. Okavango Dyke Swarm extent modified after Botswana Geoscience Information Portal and Risk-Based Solutions (RBS), 2022. Graben faults were modified after Kinabo et al. (2007). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Ma et al., 2020). These problems include both the exploration well itself and the developed reservoir. Reactivation of old structures that intersect exploration wells and the developed reservoir is a notable concern, either via regional seismic activity, groundwater, and surface water influx or as a result of subsurface fluid injection during oil and gas recovery (Ellsworth, 2013).

The continuity and density of the Okavango Dyke Swarm (Le Gall et al., 2005) are illustrated in Fig. 3, as it crosscuts both the Okavango Graben and the ReconAfrica lease areas. Dolerite dykes control groundwater flow as both barriers and conduits (Woodford and Chevallier, 2002; Babiker and Gudmundsson, 2004). Commonly exhibiting no flow across the dyke, while encouraging flow adjacent to the dyke through the fractures associated with the cooling of the dyke (Murray et al., 2012). Le Gall et al. (2005) noted a 2-to-3-meter zone parallel to an Okavango dyke's margins densely populated by brittle fractures. These fractures would reduce in frequency with increasing distance from the dyke and be deduced to have formed during the dyke's emplacement. The proximity of the dykes, along with the Okavango basin structures that crosscut and displaces the dykes (Kinabo et al., 2007), would likely lead to a higher degree of interconnectivity between the fracture zones along the dykes.

The flow velocity next to a dolerite dyke is controlled by the hydraulic head difference along the fracture zone, with the flow in the direction of the lower hydraulic head. Tracer tests performed by van Wyk and Witthueser (2011) estimated flow velocities in the fractured zone next to a Karoo dyke to range between 0.0036- and 0.29 m per second.

3. Methods and analysis: Mapping potential groundwater contamination

Groundwater data can be used to determine the piezometric surface of shallow aquifers (Boulton et al., 2007: Lamontagne et al., 2005), which in turn can be used to determine groundwater flow directions and calculate hydraulic gradients and groundwater velocity flows (Stiegeler, 1976).

Public data from 1949 to 2021 from the Department of Water Affairs in Botswana lists 2314 boreholes in Ngamiland. The Ministry of Agriculture, Water, and Land Reform in Namibia lists 1054 boreholes in the Kavango Province of the country. This data includes location, depth, elevation, drill date, and water rest level. This study limited its assessment to the 2009–2010 season, which contained the most complete and relevant dataset for assessing groundwater flows. Within this date range, 55 boreholes were available - 42 in Namibia and 13 in Botswana.

The elevation of each borehole was calculated with a 1m accuracy by using a 30-m Digital Elevation Model (DEM) from the Food and Agriculture Organization for the CORB. The borehole elevation and the rest water levels of the boreholes were used to determine the piezometric surface of the shallow aquifer system. A digital elevation model for groundwater elevation of the study area was created in Surfer (version 23.3.202) using Kriging, the most appropriate interpolation method for determining groundwater contours (Theodossiou and Latinopoulos, 2006; Gundogdu and Guney, 2007). A spatial analysis flow direction tool from the hydrological toolset within ArcGIS (version 10.8.1) was used to calculate and create a raster of the groundwater flow directions of each cell.

Groundwater flow results indicate that the groundwater could flow from the lease area to the riverbed along several vector flow lines. Hydraulic gradients were determined for specific groundwater elevation points at specific drill sites where the groundwater flow direction is towards the riverbed.

Using the hydraulic gradient for a specific flowpath, the Darcy flow velocity can be calculated using Darcy's Law (Yeh, 1981), as:

$$q = -K \nabla h$$

Where q is the flow velocity through a porous medium, K is the hydraulic conductivity, and ∇h is the hydraulic gradient.

The Darcy flow velocity applies to the cross-sectional area that moves in the direction of groundwater flow (Bear, 2012). To generate the average linear groundwater velocity, which is described as the average horizontal velocity of groundwater along a flowline (Freethey et al., 1994), the Darcy velocity is divided by the porosity of the medium through which the liquid flows.

Within the Okavango region, the hydraulic conductivity of the shallow water aquifer has been approximated in the range of 1.2*10ˆ-4 to 3.5*10ˆ-4 m/s with an average porosity of 0.30 (30%) throughout the area (Obakeng and Gieske, 1997; Wolski and Savenije, 2006). This study calculated a median range of hydraulic conductivity of 2.35*10ˆ-4 m/s. Given the similar geology of the Tsodilo area and Kavango province, we can assume the porosity and transmissivity of soils in the Tsodilo area to be similar to those found in the Obakeng and Gieske study (1997).

To determine the average linear groundwater velocity and the time it could take for contaminants to travel through the aquifer, sites within the study area that lie along flow lines to high-risk areas in the Okavango River system were used. Eight sites were selected, including two boreholes adjacent to the ReconAfrica test drill sites in Namibia and six additional borehole sites - two from Namibia and four from Botswana. Flow velocities were calculated from four sites in each lease area to rivers in the Okavango system, as defined by the groundwater directional flows. The hydraulic gradients (∇h) were calculated as:

$$\nabla h = (h_2 - h_1)/d$$

Where ∇h is the Hydraulic Gradient, h_2 is the downgradient head, h_1 is the upgradient head, and d is the distance between the wells. The average linear velocity is defined as:

$$v = q/n_e$$

Where v is velocity, q is the flow velocity through a porous medium, and n_e is the porosity of the aquifer.

The downgradient head in the CORB was calculated using the closest approximate value of the groundwater head elevation based on the DEM that was developed in Surfer. The hydraulic gradient along the flow direction from these test sites was calculated for the CORB using the transmissivity and porosity determined by Obakeng and Gieske (1997). Groundwater head elevations can be used to approximate hydraulic heads and gradients (Rankin et al., 2012: McKenzie et al., 2010; Münch and Conrad, 2007; Soriano et al., 2020). To produce a more accurate groundwater elevation map, groundwater temperatures, and flow tests would be needed at a representative resolution throughout the region (Nistor et al., 2020).

We also obtained information on the regional geology and structures; of particular interest are the Okavango Graben and the Okavango Dyke Swarm. Calculating the travel time for a contaminant to migrate in a complex fracture network from the ReconAfrica lease areas to the Okavango Graben is not feasible with the current data available. There is a significant lack of information on the subsurface geology and hydrogeology over the 320-km distance that separates the Namibian ReconAfrica lease area and the Okavango Graben. As a result, sufficient information is not available to construct a groundwater flow model, or to investigate the connectivity and flow velocities along structures that have been mostly inferred from geophysical surveys.

Rather, a range of values is used to illustrate possible travel times in a worst-case scenario where a single fracture zone with an averaged groundwater flow velocity extends over the entire 320-km distance. The hypothetical fracture will only be attributed a length and a constant flow velocity, which is used to calculate the travel time. This example does not consider fracture thickness, water volumes, or quality. The lack of field data requires the use of literature values for the proposed flow velocity, a range of velocities from 0.001 m/s to 1 m/s is used based on pumping tests performed next to a Karoo dolerite dyke (van Wyk and

Witthueser, 2011). The travel time is calculated as follows:

$$t = d / v$$

Where t is the travel time, d is the total distance that has to be travelled and v is the flow velocity inside the fracture zone.

4. Results

The groundwater flow via the shallow sandy aquifer in Botswana shows a distinctive flow from the Botswana lease area toward the Okavango River Basin (Fig. 4). In the Namibian lease area, there is a groundwater divide along the boundary of the Omatako and Okavango Subbasins. This groundwater divide is approximately 27 km east of Rundu. On the eastern side of the lease area, the groundwater flow direction is towards the Okavango River. On the western side of the lease area, the groundwater flow direction is towards the Cubango River (Fig. 4). However, groundwater can cross this divide if the hydraulic head difference within structures (dykes, faults, and fractures) or deeper-lying aquifers creates a gradient for flow in that direction. Groundwater flow directions also indicate possible groundwater flows alongside the Okavango River in the panhandle of Botswana until it reaches the Okavango Delta, at which point the directional flow proceeds into the Okavango Delta (Fig. 4).

These results indicate that the groundwater in the Botswana lease area flows directly into the western margin of the Okavango Delta, where Milzow et al. (2009) confirmed SW-GW interactions for this area based on isotopic analyses.

The calculated time for groundwater to travel from the selected sites in the lease areas to the Okavango River system via the shallow sandy aquifer is rapid, given the high hydraulic properties of the aquifer. Contamination from the West Kavango province in Namibia could infiltrate the river system along the Cubango River, moving towards the Okavango Delta (Fig. 5). Contamination from the Botswana lease area could reach the Okavango River system's most sensitive area along the Okavango Delta's western flank, where SW-GW interaction is most likely. Contamination from the Site D area in East Kavango could take 1.2 years to reach the Okavango River (Table 1), and contaminated groundwater from Site E was calculated to take only 3.4 years to reach the most sensitive area of the Okavango River system.

Travel time along fractured zones associated with geological structures is expected to be significantly faster than groundwater movement through porous media. The travel time for a hypothetical, continuous fracture zone that spans the 320-km distance between the ReconAfrica exploration wells and the Okavango Delta (Fig. 6) is calculated based on adapted and extended flow velocities from literature (van Wyk and Witthueser, 2011). This method is considered a worst-case scenario due to the continuity of the envisaged fracture zone. The resulting travel time ranges from approximately ten years with a flow velocity of 0.001 m/s, to 4 days with a flow velocity of 1 m/s.

5. Discussion

Our results indicate that a groundwater divide exists along the boundary of the Omatako and Okavango Subbasins in the Namibian lease area. Shallow contaminated groundwater west of the divide should flow toward the Cubango River, while shallow groundwater contamination on the east should flow toward the Okavango River (Figs. 4 and 5). The chances of surface and groundwater contamination within a local context are high, considering the geological structures that can serve as preferential flowpaths.

The pervasiveness of the Okavango Dyke Swarm and faults cross-cutting the ReconAfrica lease areas and the Okavango Basin creates a complex network of interconnected structures. Furthermore, active tectonic processes in the area could reactivate or modify these structures. The main tectonic force is either transtensional or extensional, which could facilitate the "opening" of faults and fractures. The

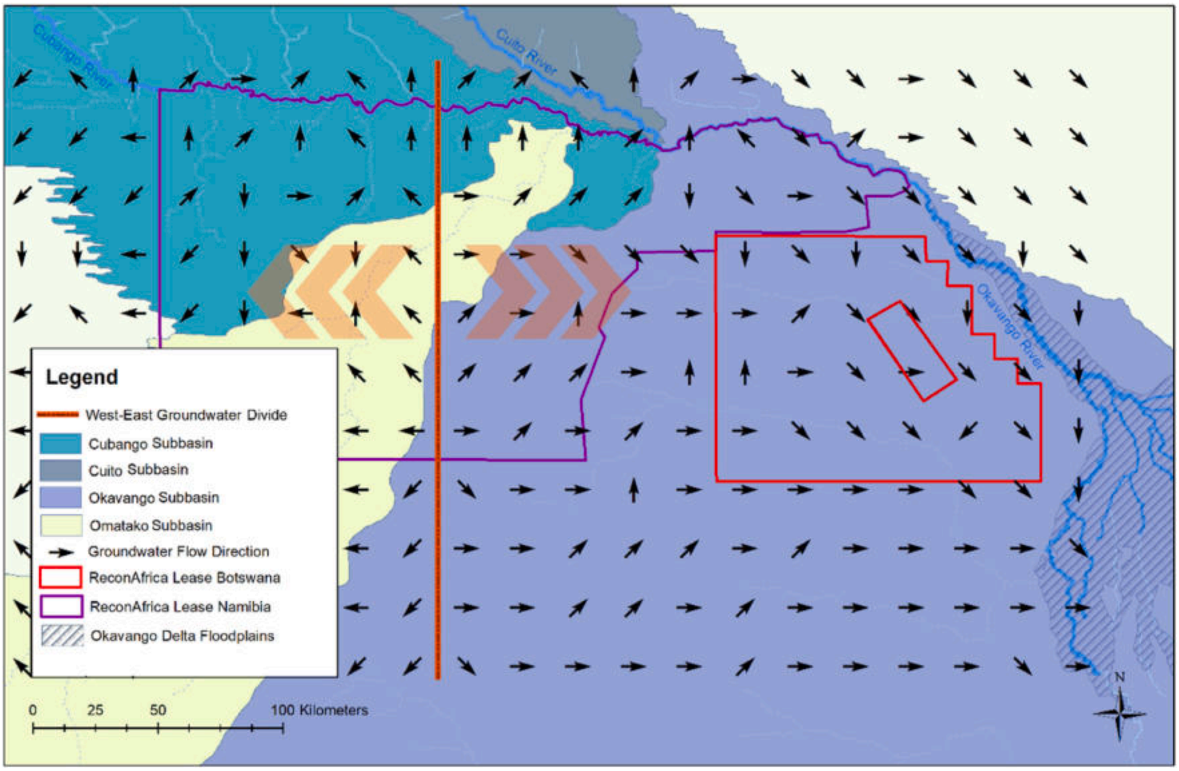

Fig. 4. Groundwater directional flows of the shallow water aquifer demonstrate a West-East Groundwater Divide mapped with the CORB subbasins and the ReconAfrica Botswana lease area in red and the ReconAfrica Namibia lease area in purple. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

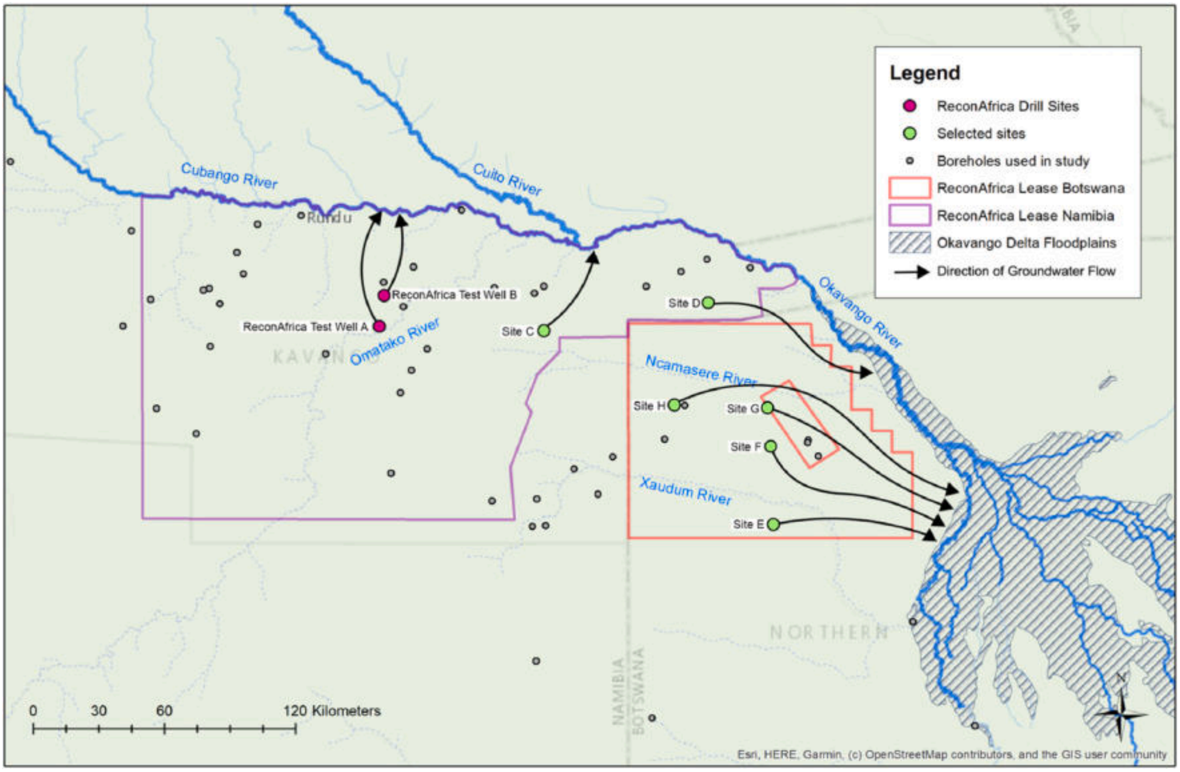

Fig. 5. Selected test sites for groundwater flow velocity determination and directional flow towards the Okavango River system, mapped with boreholes used in the study. The ReconAfrica Botswana lease is red, and the ReconAfrica Namibian lease is purple. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Hydraulic gradients, groundwater velocity, and contamination time frame from selected well sites in ReconAfrica lease areas to the Okavango River system.

Site	Distance to Okavango River system (m)	Hydraulic gradient ∇h	Average Darcy Velocity (m/d) [range]	Average linear groundwater velocity (m/d) [range]	Timeframe for contamination to reach the Okavango River system (Years) [range]
Recon Well A	52000	−0.00113	0.023 [0.012–0.034]	0.077 [0.039–0.114]	10.9 [5.6–16.3]
Recon Well B	65000	−0.00077	0.016 [0.008–0.023]	0.052 [0.027–0.078]	9.33 [4.7–13.8]
Site C	41000	−0.00061	0.012 [0.006–0.018]	0.041 [0.021–0.061]	4.6 [2.4–6.9]
Site D	66000	−0.00024	0.005 [0.003–0.007]	0.016 [0.008–0.024]	3 [1.5–4.4]
Site E	79000	−0.00058	0.012 [0.006–0.018]	0.039 [0.02–0.059]	8.5 [4.4–12.7]
Site F	74000	−0.00126	0.026 [0.013–0.038]	0.085 [0.043–0.127]	17.2 [8.8–25.7]
Site G	76000	−0.00115	0.023 [0.012–0.035]	0.078 [0.040–0.116]	16.2 [8.3–24.1]
Site H	85000	−0.00149	0.030 [0.015–0.045]	0.101[0.052–0.151]	23.5 [12–35.1]

geological structures could provide a pathway for possible contaminants to migrate to the Okavango Basin or the near-surface and the shallow aquifers within the basin. Given a worst-case scenario where a single continuous fracture connects a contamination source to the Okavango Basin receptor, with a constant flow rate of 1 m/s and a distance of 320 km, contaminants can reach the receptor in as little as four days.

The risk is not only limited to a structural pathway existing directly between the ReconAfrica lease areas and the graben, the effects of structures on the exploration wells are also significant. Structures that intersect these features could allow for the migration of contaminants to the Kalahari sands and the shallow aquifers hosted within. Structures that create pathways from the wells to the Okavango Graben, could exist. The seismic activity also poses a risk and fault movement can jeopardise the integrity of exploration wells, resulting in the possible escape of contaminants (Kang et al., 2019). We suggest that petroleum exploration poses a high risk to the Okavango Delta environment through the structures associated with the Okavango Graben and other regional structures.

Oil extraction in the lease areas could present a high risk to the health of the ecosystem, biodiversity, and human health and well-being in the region, given the detrimental effects of UOG contaminants on wetland ecosystems (Lindén and Pålsson, 2013; Hossack et al., 2018; Konkel, 2016; Ite et al., 2018; Nnoli et al., 2021; Onyena and Sam, 2020; (Raimi et al., 2022); Giadom and Tse, 2014). Possible SW-GW interaction along the lease areas into the Western flank of the Okavango Delta (Milzow et al., 2009), where geological structures provide possible preferential groundwater flowpaths, and the fact that the Okavango Delta is a terminal sink (Milzow et al., 2009) with a fragile ecosystem that could be destabilised by both surface and groundwater contaminants (Gondwe et al., 2021), exacerbates this risk.

The approximation of groundwater elevation, hydraulic head, and gradients using borehole data is not definitive, however, it is considered a reliable method and tool (Rankin et al., 2012: McKenzie et al., 2010; Münch and Conrad, 2007; Soriano et al., 2020). While this study was only able to use open-source data, a more accurate model of the groundwater elevation, groundwater temperatures, and flow direction

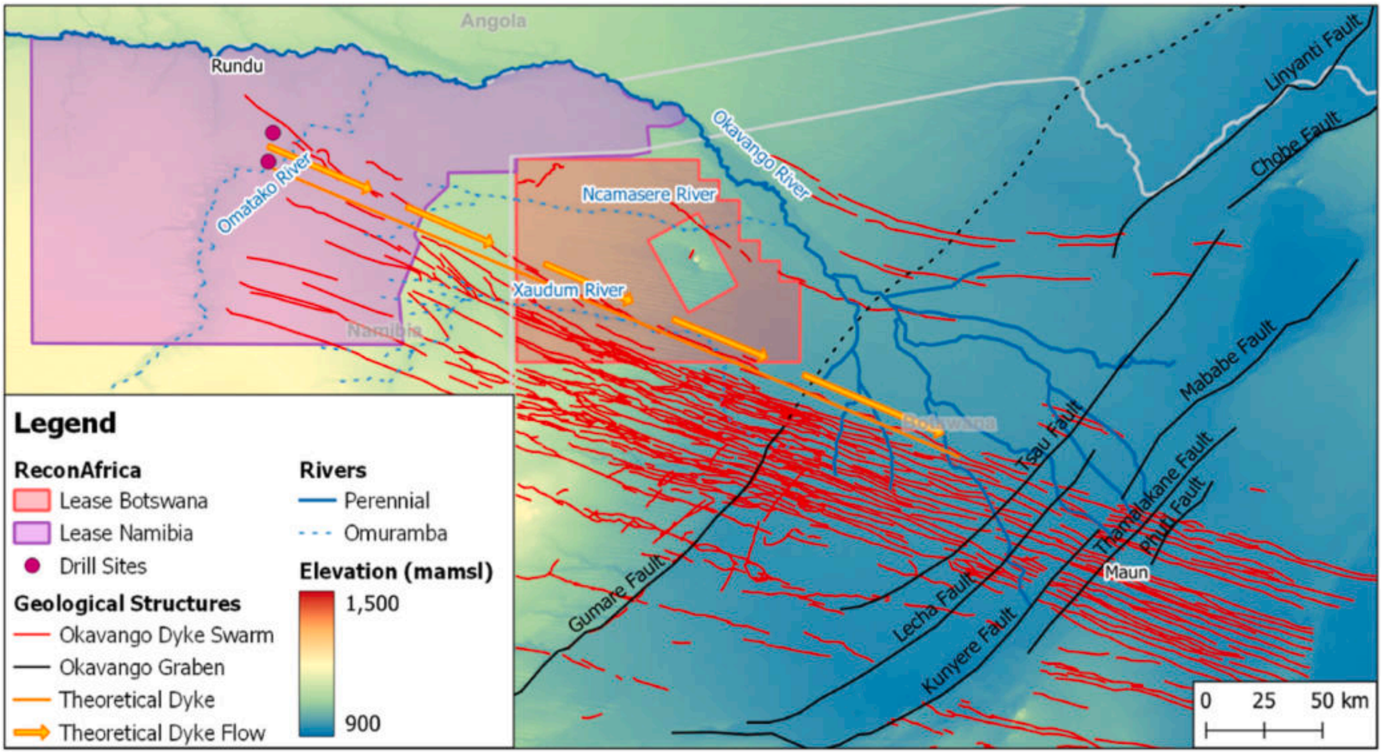

Fig. 6. Theoretical Okavango Dyke Swarm fracture zone with directional flow towards the Okavango River system. The ReconAfrica Botswana lease is shown in red and the ReconAfrica Namibian lease is in purple. The ReconAfrica drill sites are indicated with purple points. Okavango Dyke Swarm extent modified after Botswana Geoscience Information Portal and Risk-Based Solutions (RBS), 2022. Graben faults modified after Kinabo et al. (2007). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

could be achieved by collecting data from piezometers at several different sites throughout the region (Nistor et al., 2020).

Further studies are urgently needed to improve the understanding of the nature of the shallow aquifer in the region and the contamination risk posed to localised and regional ecosystems and communities. The transboundary collaborative study spearheaded by OKACOM (OKACOM, 2021) could produce a regional groundwater baseline and a more accurate groundwater model which can be used for risk assessments. The studies should include chemical analysis of the groundwater and sediments. Strategically placed borehole piezometers should measure groundwater temperatures, pressure, flow direction, and flow velocity. Tracer tests should also be done to calculate contamination directional flow and velocity throughout the relevant aquifer systems. Detailed studies on geological structures that may influence the groundwater flow are also required.

A framework for future studies should be carefully defined. Our paper presents an initial groundwater vulnerability assessment with several assumptions and limitations. Due to the limited available groundwater information, our analysis assumes homogeneous and isotropic aquifer conditions. Our study only provides analytical calculations to illustrate the possible contamination risk from UOG extraction in this area and not a numerical model. The limited available structural data, and the significant difference in the available geological data between Namibia and Botswana, also preclude including hard rock geology in a numerical groundwater model. Detailed geological and groundwater data must be generated and analysed to address the current data limitations. The contaminants from UOG extraction must be better understood regarding interaction with aquifer materials (Witkowski et al., 2004). It would be essential to study how specific organics used in the fracking and drilling fluids travel through the aquifers in the ReconAfrica lease areas. Groundwater monitoring in the oil and gas target areas would significantly improve our understanding of how contaminants could travel within the groundwater system.

Once a more robust groundwater monitoring system and vulnerability assessment has been implemented, a groundwater pollution risk assessment would be required to inform the regional governments' legal and environmental framework and OKACOM. Even though such assessments are considerably more complex and use hydrological software such as MODFLOW and DRASTIC (Barbulescu, 2020), they are more robust and useful in forming environmental policy for the long-term benefit of ecosystems, biodiversity, and human health (Witkowski et al., 2004).

This study illustrates the threats that oil and gas exploration and production pose to the water resources in Namibia and Botswana's target oil and gas areas. Oil exploration activities in the region should ideally be halted until detailed risk assessment studies of the water resources are completed. The governments of Botswana and Namibia should protect the communities, biodiversity, and the health of regional ecosystems during oil extraction by requiring rigorous EIAs before permitting any oil exploration. Until such a time as further studies are made, OKACOM should also consider imposing a moratorium on all oil and gas exploration and production within the CORB.

Author contributions

R.S. conceived the research idea, and S.G. and S.E. developed the idea further. R.S. executed the research and wrote the manuscript. S.G. and S.E. co-wrote the manuscript and reviewed and edited the final version of the manuscript. A.L. co-wrote and developed maps for the manuscript.

Declaration of competing interest

The authors declare no conflict of interest.

Data availability

Data will be made available on request.

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