Proposed Limestone Quarry on Andros, The Bahamas
Scientific Briefing Note on the Environmental Risks

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Introduction

This report was developed between 2022 and 2025 by a team of volunteer scientists, with support from the American Geophysical Union's *Thriving Earth Exchange*, the Environmental Defense Fund, and the Community and College Partners Program.

The primary aim of this document is to inform Bahamian policymakers and community members about:

1. The scientific, ecological, and cultural significance of the natural resources and ecosystems across Andros;
2. The potential risks that limestone mining poses to Andros, the Bahamas, and global systems; and
3. Viable, sustainable economic alternatives to mining on Andros.

The report is organized into five key sections that explore these issues in depth:

- *The Mining Environment*
- *The Freshwater Environment*
- *The Terrestrial Environment*
- *The Coastal Environment*
- *Building Resilience: The Human Connection*

Key findings from each section are summarized at the beginning of this document.

It is important to note that no new field-based scientific research was conducted for this report. The findings contained within this document are based entirely on a review of existing literature and other existing international expertise.

We extend our sincere gratitude to the communities of Andros for their guidance and review of this work. This report would not have been possible without them.

Highlights

The Mining Environment

The Mining Environment

Geology of Andros

Andros sits atop a limestone platform in the Caribbean formed by marine plants and animals secreting calcium carbonate ($CaCO_3$) minerals over 150 million years. Over time, these deposits were compressed to form limestone, a commercially valuable rock used in various industrial processes. Slightly acidic water traveling through fractures in the limestone dissolves the bedrock and creates karst features like caves, blue holes, and springs.

Limestone Mining Process

The limestone mining process consists of four major phases: exploration; project development; operation; and closure. Each phase involves a series of steps that can drastically alter the surrounding environment.

Limestone Mining Impacts

<u>Permanent Landscape Change</u>: Deforestation required to mine limestone will result in a loss of habitat and protection from coastal storm events. Permanent open pits up to 24 m deep will remain after mining operations cease. Mining in karst will result in sinkholes forming around and beyond the mine site.

<u>Water Changes</u>: Mining contaminants pollute water sources. Dewatering quarries causes both freshwater loss and extreme flooding downstream of where water is discharged.

<u>Noise and Vibration</u>: Mine workers and nearby residents are at increased risk of noise-related health issues. Vibrations from blasting can lead to cave collapse and foundation cracking.

<u>Dust and Emissions</u>: Dust from mining can cause health issues for wildlife and people. Gaseous emissions from machinery can also cause health problems and exacerbate climate impacts like sea level rise that will immediately affect low-lying islands like Andros.
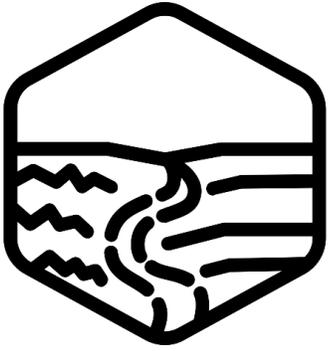
The Freshwater Environment

The Freshwater Environment

Freshwater Resources on Andros

The freshwater lens (FWL) on Andros has been used as a fresh water supply both locally and elsewhere for many decades. Water quality within the FWL is relatively steady throughout the year with little seasonal change in salt concentration between wet and dry seasons. Overall, the FWL on Andros is relatively resilient to climate change and extreme weather-related events.

Protecting Freshwater Resources

The FWL on Andros should be protected to avoid a significant loss of freshwater resources from salinization due to upward vertical migration of the saline water beneath and surrounding the quarries. The exposed surface water pits/'lakes' will act as open conduits for vertical saltwater intrusion without the added protection of surface soils. As a result, mining impacts could lead to chronic salinization with lasting effects on nearby ecosystems long after mining has stopped.

Protecting Water Quality

Changes in salinity will subsequently alter other aspects of groundwater quality (e.g., macro-nutrients and micro-nutrients, sulphate and oxygen), which can negatively impact natural biological and chemical processes. Entirely new classes of water contaminants also can be introduced during mining site preparation, extraction, and processing phases. In a karst environment, contaminated water can travel especially quickly through fractures and spaces in the rock to areas well beyond the mine site.

Preserving Natural Water Features

The ecology of and ecosystem services provided by blue holes are threatened by changes to freshwater quality and quantity induced by mining. Blue holes proximal to the mining pits (e.g., Uncle Charlie's Blue Hole) are particularly at risk. Even slight changes to organic matter inputs and water flow could have large impacts on blue hole ecology in the Bahamas.

The Terrestrial Environment

**Ecological Importance of Terrestrial Habitats**

Andros is home to diverse and unique terrestrial habitats, including Caribbean Pine forests, broadleaf coppices, and shrublands, which support rich biodiversity, including many endemic species. These forests offer essential ecological benefits like carbon sequestration and critical habitat, as well as economic benefits from ecotourism, particularly birding.

Threats to Terrestrial Species and Ecosystems

Mining operations pose significant risks to Andros' endemic and endangered species, such as the Bahama Oriole, Kirtland's Warbler, and the Andros Iguana, by destroying critical habitats and contributing to deforestation, noise pollution, and habitat fragmentation. These impacts could lead to species extinction, economic losses, and greater vulnerability to the consequences of climate change.

Degradation of Forest and Soil Health from Mining Activities

Mining operations will cause widespread damage to terrestrial ecosystems, including deforestation, soil degradation, and pollution. Removal of topsoil, sediment and dust pollution, and degradation of soil quality will have long-term negative effects on ecosystem health, carbon storage, and biodiversity. The impacts to forest and soil health are not easily reversed through existing reclamation methods.
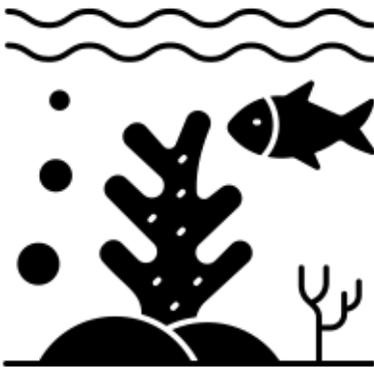
The Terrestrial Environment

The Coastal Environment

Maintaining Critical Habitats and Biodiversity

Mining operations threaten coastal marine environments that provide habitat for valuable species. Biodiversity could dramatically decline in response to habitat degradation, noise from mining operations, and transport vessels - which strike wildlife, and introduce invasive species.

Flood and Storm Resilience

Maintaining coastal habitats is critical for outpacing sea level rise and mitigating coastal flood hazards which are increasing in frequency and intensity as climate change progresses

The Coastal Environment
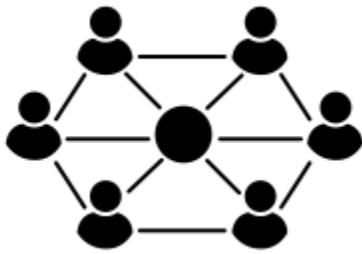
Building Resilience: The Human Connection

Building Resilience: The Human Connection

Human Health and Well-being

Both mine workers and residents living near the mine sites are at risk of a wide array of physical and mental health hazards caused by noise, dust, noxious emissions, ground vibration, environmental degradation, water scarcity, and sexual violence.

Future Water Security

Andros has the largest freshwater lens (FWL) in The Bahamas. Its large size offers greater resilience compared to smaller FWLs on other islands that have significantly deteriorated due to extreme climate events. The FWL on Andros is a gift of nature. It has the potential to provide The Bahamas with a long-term sustainable water resource into the future that does not rely on the expensive and harmful alternative of burning fossil fuels for desalinization.

Future Food Security

Andros has the largest percentage of agricultural land in The Bahamas. As climate change destabilizes food systems, it is all the more important to have local, sustainable agriculture and fisheries.

Sustainable and Climate-Prepared Economy

By preserving blue carbon ecosystems (i.e., seagrass, coral) and designating protected areas, the Bahamas may be eligible for carbon credits and will safeguard food sustainability for future generations. Sustainable ecotourism opportunities can also be leveraged as conservation and livelihood diversification strategies, and empower local communities in environmental and economic decision-making.

<table>
<tr><td></td><td>## The Mining Environment</td></tr>
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Geologic Context and Mining Area

Andros is made up of a low-lying set of limestone cays and islands that sit atop a 5 to 10 km thick carbonate platform in the Caribbean (Curran et al., 1997). These deposits were formed by marine plants and animals secreting calcium carbonate ($CaCO_3$) minerals over 150 million years. Over time, these deposits were compressed to form limestone, a commercially valuable rock used in various industrial processes. Because of its geologic setting, Andros is characterized by karst terrain. Karst topography forms over thousands of years as a result of slightly acidic water traveling through fractures in carbonate rock, thus dissolving it (Langer, 2001; Waele, 2017). This dissolution of bedrock creates features like caves, sinkholes, springs, and sinking streams (Langer, 2001; Soni and Nema, 2021) (Figure 1).
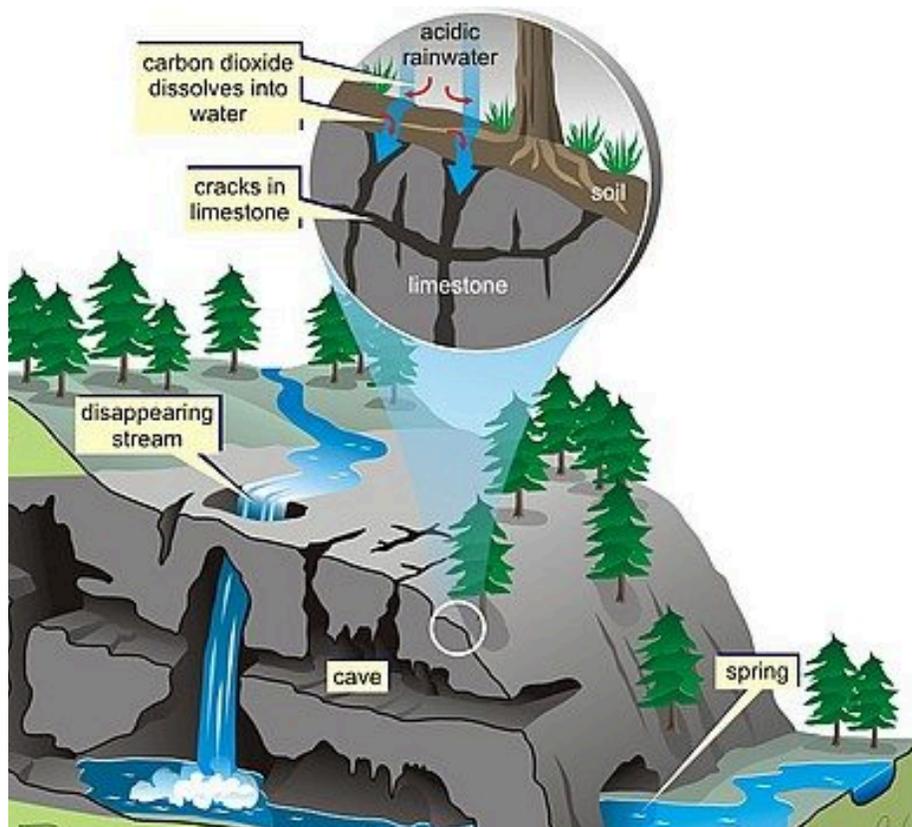

Figure 1. Diagram showing karst topography (from McColl et al., 2005).

The limestone on North Andros is of high quality and there has been interest in mining it for several decades. The proposed limestone mining operation will occur in the northern tip of North Andros (Figure 2). Two quarries are proposed and would cover a total area of 6,000 acres if excavated.
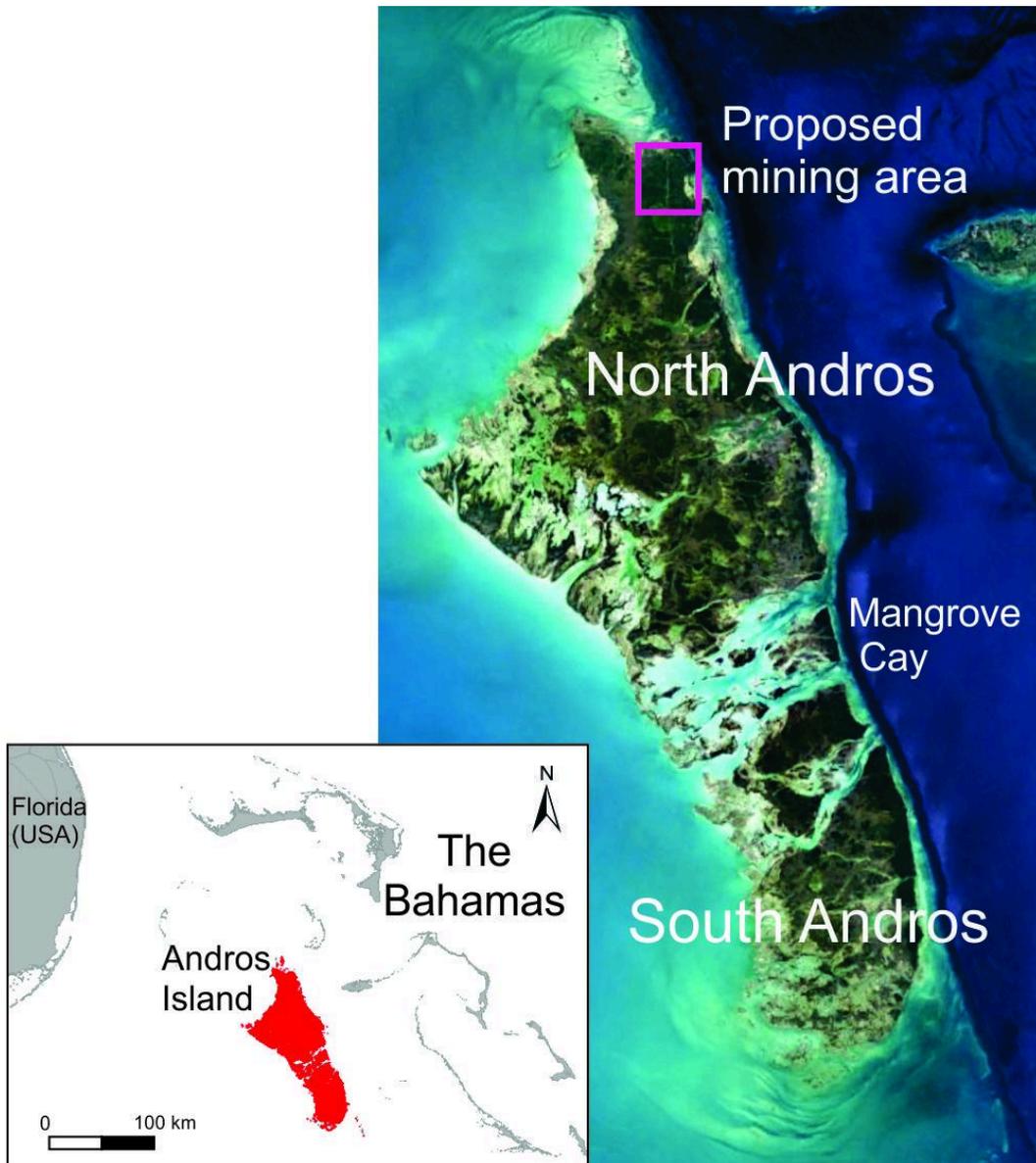

Figure 2. Map of Andros Island showing the proposed mining area in pink (base map from Google Earth).

Limestone Mining Process

The limestone mining process consists of four major phases: exploration; project development; operation; and closure (Ganapathi and Phukan, 2020). Each phase consists of a further series of steps.

Exploration is the process by which geologic resources are located and identified for extraction. In the early stages of exploration, existing information about limestone in the region is reviewed. Preliminary information

often comes in the form of geologic maps, which show lateral extents of rock types in an area. Additional minimally invasive methods may be used for further exploration before turning to invasive techniques, like drilling into the ground. Minimally invasive methods of determining the location and extent of the limestone include aerial photographs, remote sensed imagery, and geophysical surveys that can reveal further information about rock properties below the surface (Marjoribanks, 2010). After minimally invasive techniques are exhausted, increasingly invasive methods of exploration are used. Samples of rock and soil in the area(s) of interest are taken for geochemical analysis to reveal more information about the rock, like composition. Following small-scale sampling, larger rock cores are drilled and extracted throughout the area of interest to further develop geological knowledge and inform planning (Marjoribanks, 2010). Some pollution can be produced at this stage from land disturbance and waste. Sample wells, if not properly sealed, can be a conduit of contaminants that enter local aquifers. The karstic nature of the limestone on Andros can further distribute contaminants beyond these wells.

Project development includes development of the site by construction of roads and buildings, underground work on access tunnels, erection of treatment plants, overburden stripping and placing, preparation of disposal areas, and construction of service infrastructure such as power lines or generating plants, railways, water supplies and sewerage, laboratories and amenities. In the context of Andros, this phase would also involve dredging and developing an operational port at Morgan's Bluff. Overburden removal is required to access the limestone bedrock for quarrying. Overburden refers to material overlying the limestone which may include rock, soil, sediments, vegetation, and wildlife. Typically, bulldozers are used to strip overburden in the mining area before mining operations can begin (Soni and Nema, 2021).

The *operation* phase consists of the active extraction, processing, and transport of the mined material (Figure 3). As it is proposed, the limestone mine on North Andros would be an open-pit mine. A grid of boreholes is drilled into the limestone bedrock using rock boring machines. Explosives, like dynamite, are placed in the boreholes and detonated to break up the bedrock for removal, or excavation (Balasubramanian, 2017). After the rock has been broken up, dragline excavators are used to extract the limestone blocks from the pit. Draglines are among the largest machines ever built, typically ranging in size from 7,250 to 11,800 metric tons and 55 to 140 m in length (American Mine Services, 2021; Kohler, 2023). A large scoop attached to a long mast (boom) and cable system on the dragline is used to remove large blocks of limestone from the quarry. Big Muskie, the largest dragline excavator to ever exist, used enough electricity while operating to power 27,500 homes (American Mine Services, 2021). As rock is excavated, large and deep pits are created. The pits increase in depth and size as the cycle of drilling, blasting, loading, and hauling continues. The proposed mine in North Andros will consist of two quarries each 18 to 24 m deep. One proposed quarry will have a surface area of 1,000 acres and the other 5,000 acres. Roughly 450 to 635 million metric tons of limestone will be extracted during the lifespan of the proposed operation. As limestone is extracted from the quarries, it is hauled by trucks to a series of onsite crushers, grinders, and vibrating screens. The crushers and grinders break down the larger blocks of limestone into aggregate of various sizes of rock, gravel, and dust. Vibrating screens separate out different sizes of aggregate to prepare for transport and shipment. The aggregate is again transported by a series of conveyors to the port to be loaded onto ships and exported. For the proposed operation in North Andros, aggregate would have to be transported up to 10 km from the quarry site to Morgan's Bluff.

Figure 3. Steps of a limestone mining operation from overburden removal to export of aggregate. *Image credits: (a) Inca Mining LTD, 2021; (b) Mega Machines, 2022; (c) Aaron Fronek, 2017; (d) Midwest Crushing and Screening, 2021; (e) Gary Merrin/Rex Features, 2011; (f) Mega Machines, 2022.*

As mining operations cease, the site is prepared for **closure.** Closure typically involves remediation, restoration, reclamation, or rehabilitation (Lima et al., 2016) (Figure 4). Remediation refers to the clean-up of the mine site, with an end goal of removing contaminants before re-establishing land use (Lima et al., 2016). Restoration is a process by which the pre-mining ecosystem is restored to its original state (Lima et al., 2016). Often restoration is not possible, so mines pursue reclamation efforts. Reclamation involves recovering certain ecosystem services when a site cannot be fully restored (Lima et al., 2016). Finally, if reclamation is not a possibility, rehabilitation aims to "optimize local land management capacity and includes practices such as agriculture, forestry, and urbanization" (Lima et al., 2016, p. 229). Rehabilitation is best done progressively, rather than at the end of the life of the mine, and accordingly needs to be a part of ongoing operations. These are important and often neglected aspects of the mining process. While the closure and rehabilitation is intended to mitigate environmental impact, it is important that it does not itself create secondary effects, such as excessive fertilizer use, spread of weeds, siltation and incompatible landscape features. Ongoing monitoring and maintenance are required in many situations. Because such a large volume of limestone will be

extracted from the site on North Andros, completely restoring the landscape will not be possible. Even after backfilling the open quarries with site waste, large pits will remain and fill with water where there was once a rich coastal pine forest. These post-closure processes are extremely expensive in karstic zones (Lolcama et al., 2002).
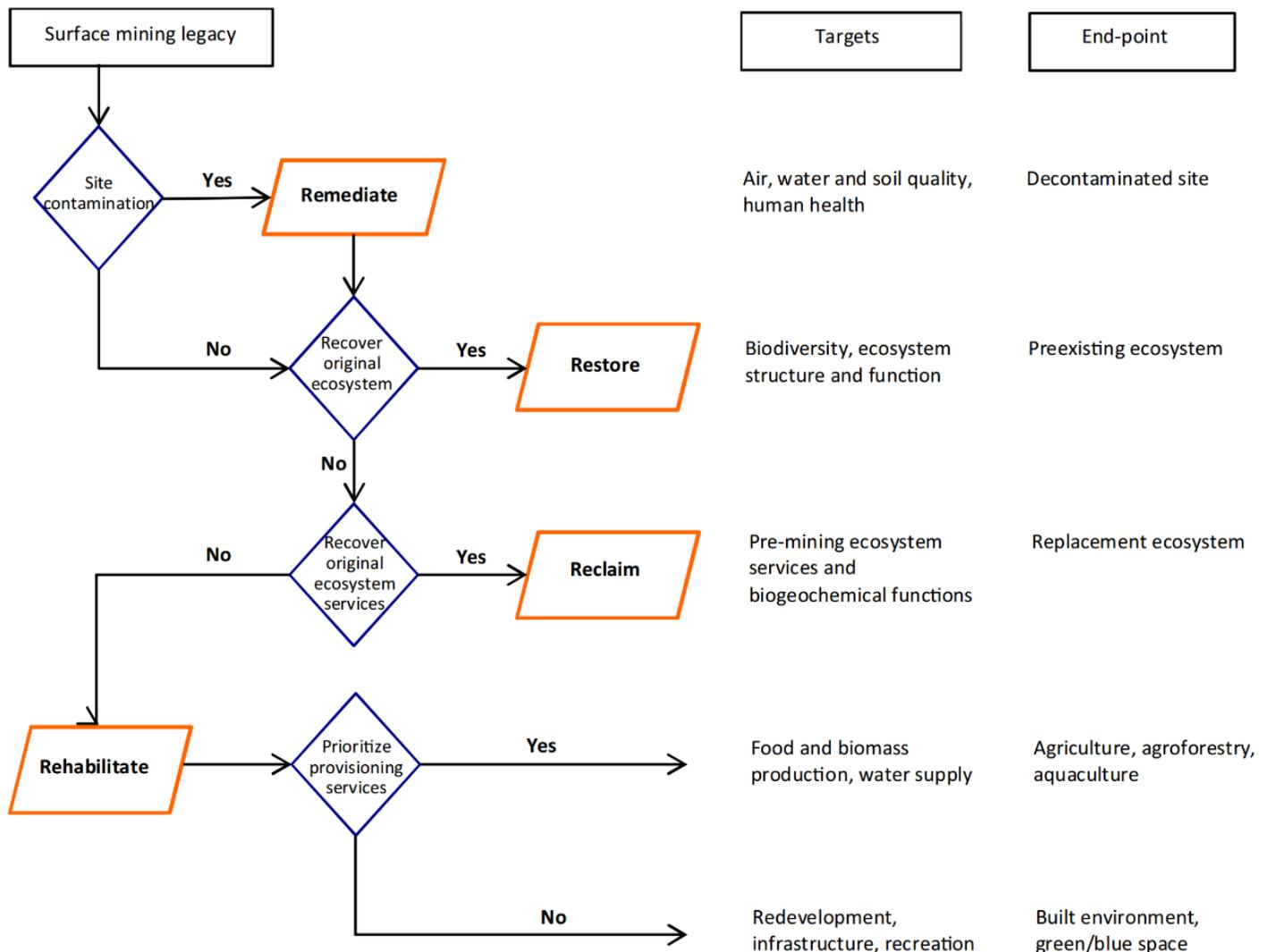
Figure 4. Decision tree based on targets and end-goals for post-mining recovery (from Lima et al., 2016).

Limestone Mining Hazards

Aggregate mining in karst terrain can have many cascading environmental impacts (Langer, 2001). Environmental impacts occur as a response to mining activities that change the natural system. As the environment responds to these changes, impacts result that create additional changes, responses, and impacts. According to Langer (2001), "Cascading impacts may be severe and affect areas well beyond the limits of the aggregate operation. Cascading impacts may manifest themselves some time after mining activities have begun and continue well after mining has ceased" (p. 8). Most limestone mining hazards are the result of cascading impacts.

Permanent Landscape Change

Limestone mining operations result in many permanent changes to the landscape (Figure 5). Deforestation occurs in the area when trees, vegetation, and soil are cleared to expose the limestone bedrock for mining. This loss of forest habitat has negative impacts on wildlife and regional biodiversity beyond the mine site as well (Arbogast et al., 2000; Ganapathi and Phukan, 2020; Wang et al., 2012). Furthermore, when lime mixed waste substances are deposited on open land during the mining operation, soil quality in those areas deteriorates (Lamare and Singh, 2016). Fertile topsoil that is removed or deteriorated from mining operations can take thousands of years to form, making it difficult (if not impossible) for trees and vegetation to grow back (Ganapathi and Phukan, 2020). Because trees and vegetation in coastal forests also serve as added protection from intense winds and storm surges during hurricane events, effects from these storms can be exacerbated inland without them.

In addition to loss of forest habitat in the mining area, two large quarries - 1,000 acres and 5,000 acres, respectively - up to 24 m deep will remain where the limestone was extracted, permanently altering the landscape. A key part of reclamation involves "turning undesirable features (quarries and pits) into something perceived as desirable by the public" (Arbogast et al., 2000). The quarries that would result from the proposed mining operation on North Andros would be wet quarries, which are quarries that fill with water and have a wet bottom. Examples of uses for reclaimed wet quarries fall into several categories: conservation, recreation, public facilities, commercial/industrial, recycling, and storage (Arbogast, 2000). Quarries reclaimed for conservation purposes often function as passive lake habitat for aquatic life and waterfowl (Arbogast, 2000). Approaches to reclamation in North Andros identified by Coastal Systems International include lakefront residences, research facilities, eco-activities like kayaking and bird watching, aquaculture facilities, and youth recreation such as swimming. It is important to note, however, that perceived desirability by the public does not equate to ecological functionality. Irreversible changes to the water quality and landscape will not support most native species that occupied the region prior to mining. Moreover, the irreversible destruction of underground cave systems during the extraction of limestone will endanger endemic species restricted to those ecosystems (Barber, 2017). This will ultimately have detrimental impacts to rich ecotourism and aquaculture opportunities in Andros. Recreational uses for reclaimed quarries typically focus around swimming and fishing. Quarry walls are very steep and must be graded near the edge to support swimming and wildlife, which is often a costly process. Even in quarries with man-made beaches, there is still a steep dropoff not far off of the quarry edge. According to Chief of Safety for Mine Safety and Health Enforcement at the U.S. Mine Safety and Health Administration, Stephen Gigliotti, "Each year, dozens of people are injured or killed while exploring, swimming or playing at a mine property" (2022). Swimming in quarries is especially risky compared to other bodies of water because the water is so cold, and slippery steep quarry walls make escape difficult (Gigliotti, 2022). Children living in residences along the quarry are at increased risk of an accident occurring.

Figure 5. Aerial photograph of a limestone quarry in Bloomington, Indiana. *Image credit: Aerial182, 2016.*

Changes to Surface and Groundwater

Impacts on freshwater resources in karst environments are of particular concern given that "karst systems have very low self-purification capabilities" (Langer, 2001, p. 14). Limestone mining operations impact both water quality and quantity (Lamare and Singh, 2016). Impacts to water quantity predominantly arise as a result of mine dewatering and discharge (Ganapathi and Phukan, 2020). Mine dewatering lowers the water table significantly and changes groundwater flow direction and amount (Figure 6). Additionally, most of the pumped water is lost from the local groundwater system entirely. Combined with increased runoff, these processes result in localized reduction of groundwater storage (Ganapathi and Phukan, 2020). Some surface water features - like streams - will dry up as the water table near the mine is lowered, while others may overflow and cause extreme flooding downstream of where pumped water is discharged (Ganapathi and Phukan, 2020). Areas around the mine site where the water table has been lowered are at increased risk of cavity formation in the rock and eventually sinkhole collapse (Lolcama et al., 2002). Additional pollutants can be introduced to the groundwater system where these sinkholes collapse (Langer, 2001). As described further in the section on The Freshwater Environment, the freshwater lens on North Andros will disappear beneath and surrounding the quarries, resulting in salinization due to mine dewatering activities.
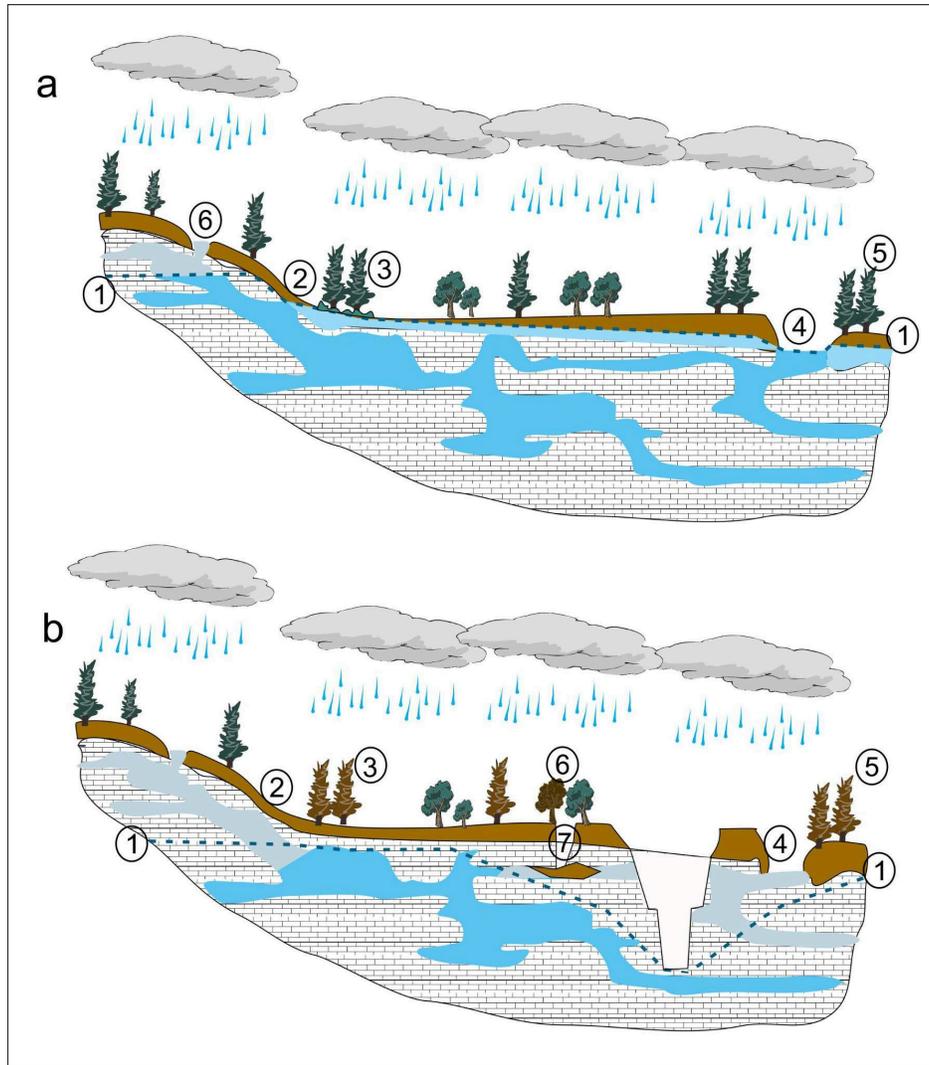
Figure 6. (a) Hypothetical cross section showing karst area under conditions prior to quarry development. The water table (1) is generally above the soil/bedrock contact. Natural groundwater discharges to a spring (2), and a perennial stream (4), which supports wetland (3) and a riparian woodland (5). A natural sinkhole occurs where the water table is below the soil/bedrock contact (6) (Langer, 2001, p. 18). (b) Hypothetical cross section showing karst area under worst-case conditions after quarry development. Under actual conditions, none, some or all of these conditions may exist. Quarry dewatering has lowered the water table (1) below the soil/bedrock contact. Natural groundwater discharge to a spring (2) and perennial stream (4) has stopped, resulting in the destruction of the wetland (3), drying up of the stream (4) and destruction of the riparian woodland (5). The ground above the cavity has subsided, resulting in the formation of a wet area, and tilting of fence posts or trees (7). Ultimately, these cavities could collapse, creating a collapse sinkhole (8) (from Langer, 2001, p. 18).

Noise and Vibration

Noise is generated by various mining activities including machine operation, drilling, blasting, excavation, truck and conveyor material transport, crushing, grinding, screening, and reclamation (Manwar et al., 2017). According to Sudhakar et al. (2022), "noise is the most common and recurring environmental stress in mining sites" following dust (p. 751). In their *Environmental, Health, and Safety Guidelines*, the World Bank specifies

maximum noise levels of 45-55 decibels (dB) in residential and institutional areas and 70 decibels in industrial and commercial areas (2007). Even so, there are negative consequences to human and environmental health at these noise levels after prolonged periods. Additionally, many studies have shown quarrying operations often exceed these levels with recorded levels of over 90 dB in the quarries (Cinar and Şensöğüt, 2019; Manwar et al., 2017; Manwar et al., 2016; Pavón and Recuero, 2006; Pantelic et al., 2023; Sudhakar et al., 2022). Noise levels upward of 80 dB have been recorded outside of a quarry along conveyors and haul roads (Manwar et al., 2017; Pantelic, 2023). Mine-related noise upwards of 50 dB has been recorded over 1 km from a limestone quarry in India (Manwar et al., 2016). A noise model of a proposed tantalum mine in Egypt predicted mine-related noise of 30 dB several kilometers from the mining site (ELnady Engineering & Agencies, 2022) (Figure 7). Mine workers and residents near the mine site are at increased risk of noise-related health issues from these noise levels. Potential health risks include hearing loss, disturbed sleep patterns, increased stress, increased risk of cardiovascular disease, and developmental, behavioral, and learning problems. This is especially concerning given the proximity of the proposed mine site to Lowe Sound Primary School, Clara Evans Primary School, and North Andros High School. Noise impacts are context-dependent and vary based on the local topography, climate, and land cover (Langer, 2001).Thus, without further study it is difficult to assess precisely how neighboring communities on North Andros may be impacted by sound. Noise impacts to the marine environment are discussed further in the section on The Coastal Environment.
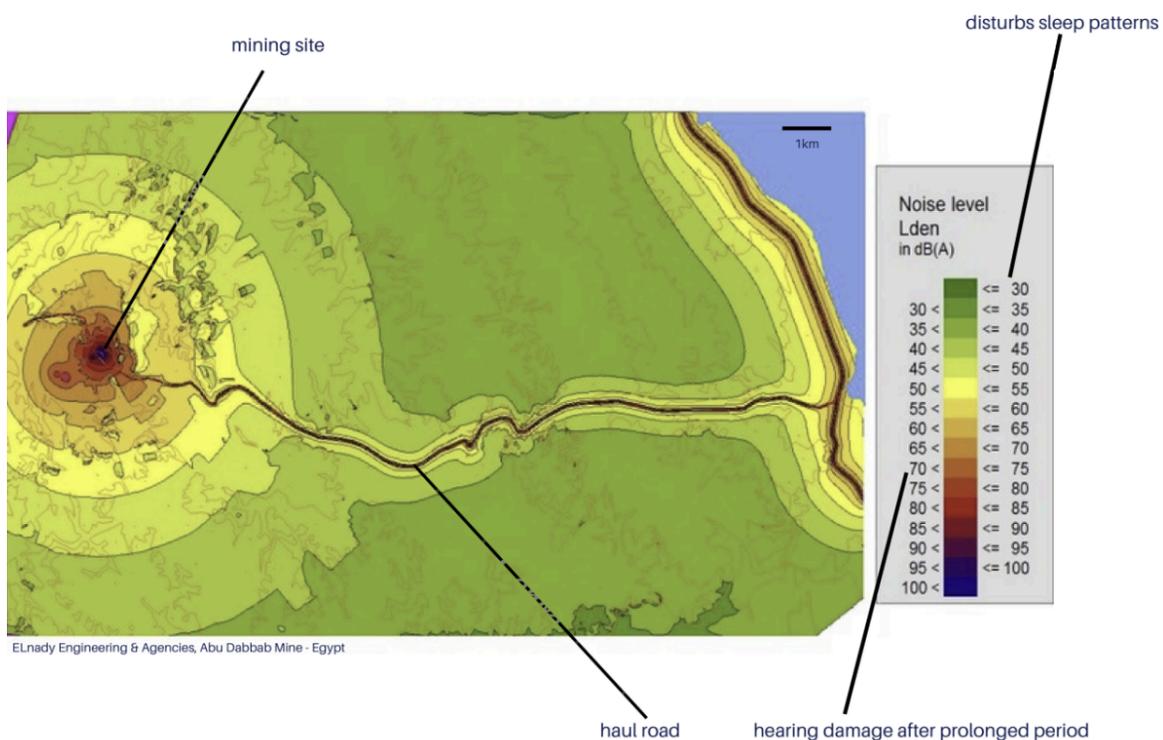
Figure 7. Modeled noise levels at the proposed Abu Dabbab Mine in Egypt (from ELnady Engineering & Agencies, 2022).

Ground vibrations produced from blasting have adverse impacts on humans and the environment like cave collapse, quarry wall instability, and cracks in building foundations (Arthur et al., 2022; Lamare and Singh, 2014). Only about 20-30% of blast energy actually breaks the rock for quarrying (Sołtys et al., 2017). The remaining energy is lost as seismic waves, airblast, and flyrock (Langer, 2001; Sołtys et al., 2017). Airblasts, seismic waves, and flyrock have potential to damage surrounding structures, both natural and manmade

(Langer, 2001; Vasović et al., 2014). If the maximum allowable airblast overpressure (140 dB) is adhered to, structural damage should be largely avoidable from airblast effects (Vasović et al., 2014). Similarly, well-detonated explosives should not produce large amounts of flyrock; however, karst terrain can increase flyrock risks (Langer, 2001). Seismic waves traveling through the ground can be mitigated but not entirely avoided. The resulting ground vibrations can be so strong that they register as low-magnitude earthquakes on the Richter Scale. Ground shaking from blasting can result in stalactites and stalagmites - mineral structures in caves that take thousands of years to form - breaking, cave and sinkhole collapse, disruption of karst biota, quarry wall fracture, and building damage (Langer, 2001). Weak or poorly maintained structures are at increased risk of experiencing damages like cracking foundations. Additionally, quarry wall fractures have been shown to initiate flooding events (Langer, 2001).

<u>Dust and Emissions</u>

Air quality in areas where limestone mining occurs is negatively impacted by limestone dust and emissions from heavy machinery. Dust is by far the most visible and invasive airborne pollutant associated with limestone mining (Barber, 2017). Dust can become suspended in the air at various points during operations including drilling, blasting, excavation, transport, crushing, and screening. Suspended dust carried by wind currents eventually settles on the ground and in water sources, negatively impacting the surrounding environment and health of local biota (Barber, 2017; Langer, 2001). Dust from limestone mining operations has been shown to negatively impact plant growth and physiology (Brandt and Rhoades, 1972; Rajwar, 1982). Additionally, despite dust levels remaining under prescribed limits, a community living near a limestone mine in India experienced increased cases of tuberculosis during the mine life (Mishra et al., 2004). Inhalation of limestone dust over long periods may contribute to chronic health issues like chronic obstructive pulmonary disease (COPD) (Suryaman and Rahman, 2011). While limestone generally has low silica composition, it can contain up to 40% crystalline silica (Mankar et al., 2019). Health impacts from silica dust exposure are well studied. One potential health problem that may arise as a result of silica dust inhalation is inhibited immune response to infection (Mankar et al., 2019). In the long-term, silicosis, a fatal lung disease, can develop in mine workers and residents near the mine site (Mankar et al., 2019). Other health issues associated with long-term silica respiration are cardiovascular disease, chronic bronchitis, lung cancer, airflow obstruction, rheumatoid arthritis, scleroderma, Sjogern's syndrome, lupus, and renal disease (Mankar et al., 2019). A health risk assessment conducted on a limestone quarry in Indonesia found that the "safe zone" from limestone dust was over 3 km from the mine site (Suryaman and Rahman, 2011). Like with noise pollution, however, dust levels are highly dependent on the specific environment in which the mining is occurring - dependent on factors like wind, topography, and climate. Similarly, further sampling and research would be needed to determine the exact composition of limestone in North Andros; however, it is unlikely that silica-related illness would be a major concern given the compositional purity of limestone in the region.

Heavy machinery produces gaseous emissions, like sulfur dioxide and carbon dioxide, that can have negative consequences on human and environmental health. Limestone mining requires extraordinary amounts of fossil fuel and electric energy. This energy use, combined with deforestation, results in increased carbon dioxide output and a loss of carbon dioxide uptake (Ganapathi and Phukan, 2020). Limestone mining is the first step to cement production, an industry which in 2010 contributed up to 8% of carbon dioxide emissions globally (Andrew, 2019). Thus, Ganapathi and Phukan (2020) state, "areas where large-scale mining activities are concentrated can contribute towards the worldwide phenomenon of climatic changes" (p. 126). Low-lying islands like Andros will be among the first to experience harmful climate impacts like sea level rise.
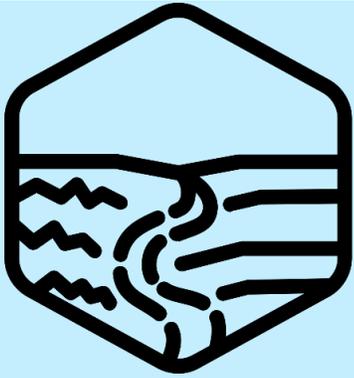
Freshwater Resources on Andros Island

Most fresh water on small islands is present as freshwater lenses (Figure 8). Freshwater lenses (FWLs) develop due to infiltrating precipitation (recharge), which is held in the subsurface (aquifer) above saline groundwater. Underlying the FWL is a mixing zone of brackish groundwater, which can vary in thickness from less than a meter to tens of meters (Falkland, 1991). The position of interface between the salt water and fresh water is described hydro-dynamically stable (Kohout, 1960), meaning that the fresh water is continually discharging to the ocean, pushing back the salt water and maintaining the geometry of the lens (Figure 8).
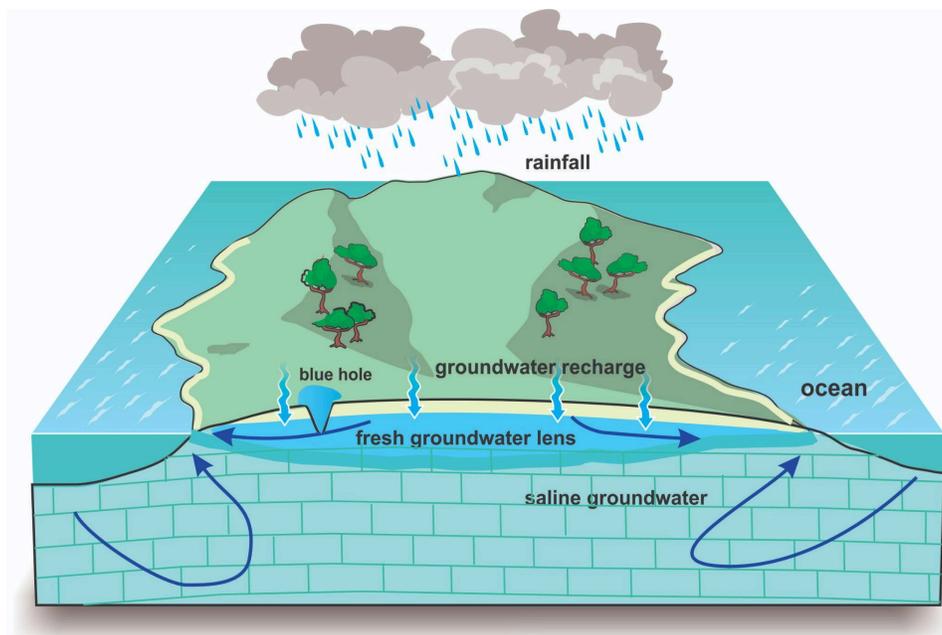
Figure 8. A freshwater lens on an island. Vertical light blue arrows show infiltration from precipitation, which replenishes the freshwater lens. The dark arrows show the groundwater flow lines in both the fresh groundwater lens and the underlying saline aquifer.

The extent and thickness of FWLs on islands depends on the island topography, geology and climate. Generally, islands that are low-lying have a relatively thin FWL. Andros is generally low-lying; the highest elevations of approximately 20 m above sea level (masl) correspond to a ridge that parallels the east coast, while the lowest elevations (<1 masl) are along the west coast. Andros, though, is large in area (relative to the other Bahamian Islands); it covers an area of approximately 14,000 km². The current extent and thickness of the FWL on Andros is uncertain because little recent information exists on the characteristics of the lens. During the 1970s, as part of a land survey, 130 boreholes were drilled into the limestone at various locations across the island (Little et al., 1973). In addition to measuring the depth to the water table in these boreholes, the salinity was measured at 1.5 m depth intervals during drilling, immediately after borehole completion, and several weeks later to determine the depth to the base of the FWL. The locations of these historical boreholes in North Andros were mapped at the time (Figure 9); however, maps showing the locations of historic boreholes in the other districts are not available. The average depth of the FWL from all 130 boreholes was 16.0 ± 7.5 meters below ground surface (mbgs). Average depth to the water table was 1.0 ± 0.8 mbgs, with maximum depth up to 5 mbgs underneath the high topography ridge. The elevations relative to mean sea level for top and base of the FWL are generally not known because ground surface elevations were not measured for the boreholes and their locations are inaccurate. However, the maximum elevation of the FWL in North Andros has been estimated to be around 2 masl (Ritzi et al., 2001). Wolfe et al. (2001) showed that the zone of brackish water between the fresh and salt water is approximately 10 m thick.
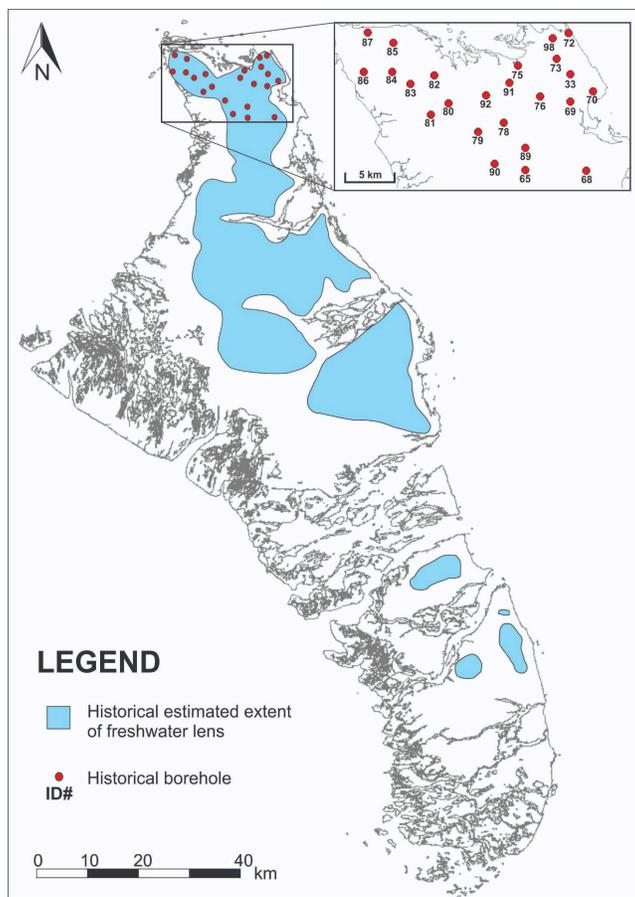

Figure 9. Historical estimate of FWL extent. The locations of historical boreholes on North Andros are shown (from Holding, 2014 using data from Little et al., 1973).

Holding (2014) used a computer model to simulate the FWL on Andros (Figure 10). To estimate the extent and thickness of the lens, two criteria were applied: 1) a lens thickness of greater than 2 m, and 2) salt concentration less than 400 mg/L. If both criteria were met, the FWL was considered viable, meaning that the FWL can provide a sustainable water supply. In general, the modeled extent and thickness of the lens corresponds to field data in areas where data are available (compare Figures 9 and 10). Holding (2014) estimated the maximum depth of the lens at around 10 mbsl and the total estimated volume is approximately 13 billion cubic meters. Along the coastlines, the simulated FWL tended to be modeled further inland than it is in reality. This is particularly evident around the Mangrove Cay and The Bluff wellfields; however, the maximum depth of the modeled FWL is generally consistent with field studies in both of those areas. For comparison, Adams et al. (2001) used a geophysical technique (resistivity) to image the FWL on North Andros. Their results show a single lens spanning the island from Red Bays on the west to Conch Sound on the east. The FWL averages about 15 m thick over much of the island, but thins to about 8 m under the well field areas, and thins to about 10 m in the vicinity of Charlie's Blue Hole.
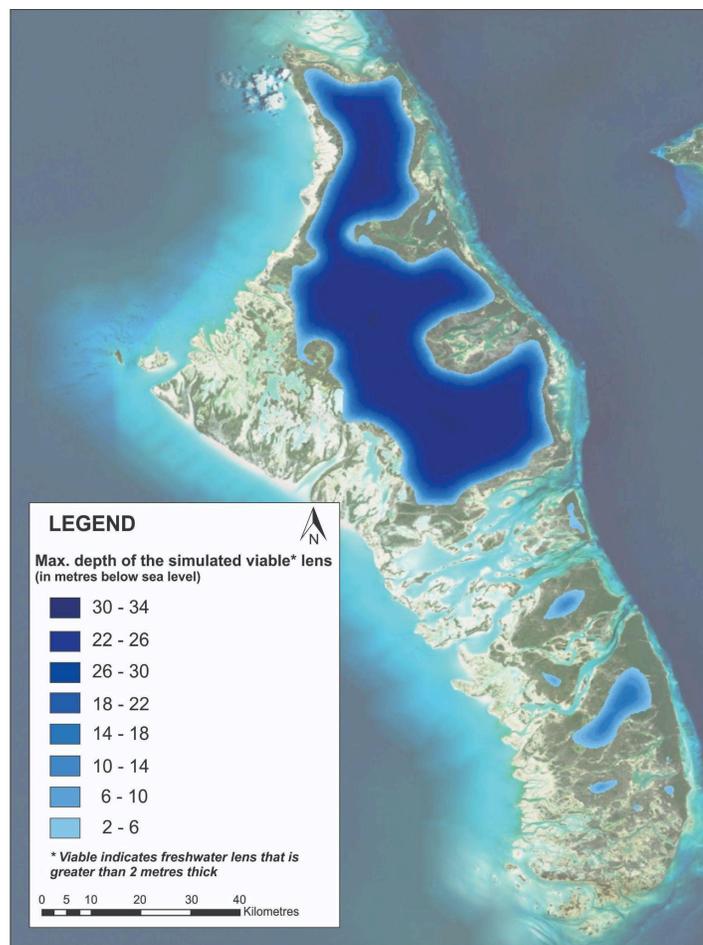
**Figure 10. Simulated viable* FWL under current (2013) conditions.
*viable means that the FWL can provide a sustainable water supply,
which is defined as having a lens thickness of greater than 2 m and salt
concentration less than 400 mg/L (from Holding, 2014).**

The FWL on Andros has been used as a fresh water supply both locally and elsewhere for many decades. On Andros, private wells are used largely for irrigation and/or industrial operations. Small, privately operated,

reverse osmosis saltwater treatment systems are used on the island to support some tourism and industrial facilities; however, these are few in number due to high operational costs (Holding, 2014). In 1977, in response to increased water demand on New Providence Island, the Water and Sewerage Corporation (WSC) began shipping water from Andros (North Andros Wellfield) to New Providence. Barged water served as more than half of New Providence's water supply with average volumes of over 21,821 m^3/day being shipped in 2000 (United States Army Corps of Engineers, 2004). Barging continued for 34 years. Currently, desalinated ocean water is the primary source of drinking water, providing 90% of the potable water on New Providence, supplemented by groundwater (Water Sewerage Corporation, 2022).

The North Andros Wellfield consists of a series of interconnected trenches used to skim water from the top of the FWL (Figure 11a). The wellfield consists of 300 m-long trenches that are approximately 1 m wide and 2 m deep (Bowleg and Allen, 2011). Each trench radiates from a central cruciform (central node connecting two or more trenches), which has a minimum of two and maximum of four trenches that drain towards the center (Figure 11b). The cruciforms situated at the northern end of the wellfield are spaced several hundreds of meters apart and are connected by culverts, whereas all limbs within the southern cruciforms are interconnected. There are a total of 35 cruciforms and approximately 40 km of trenches. During operation of the wellfield, water within each cruciform flowed by gravity to a central sump where it was pumped into reservoir tanks for treatment and distribution into the WSC water lines (Bowleg and Allen, 2011).
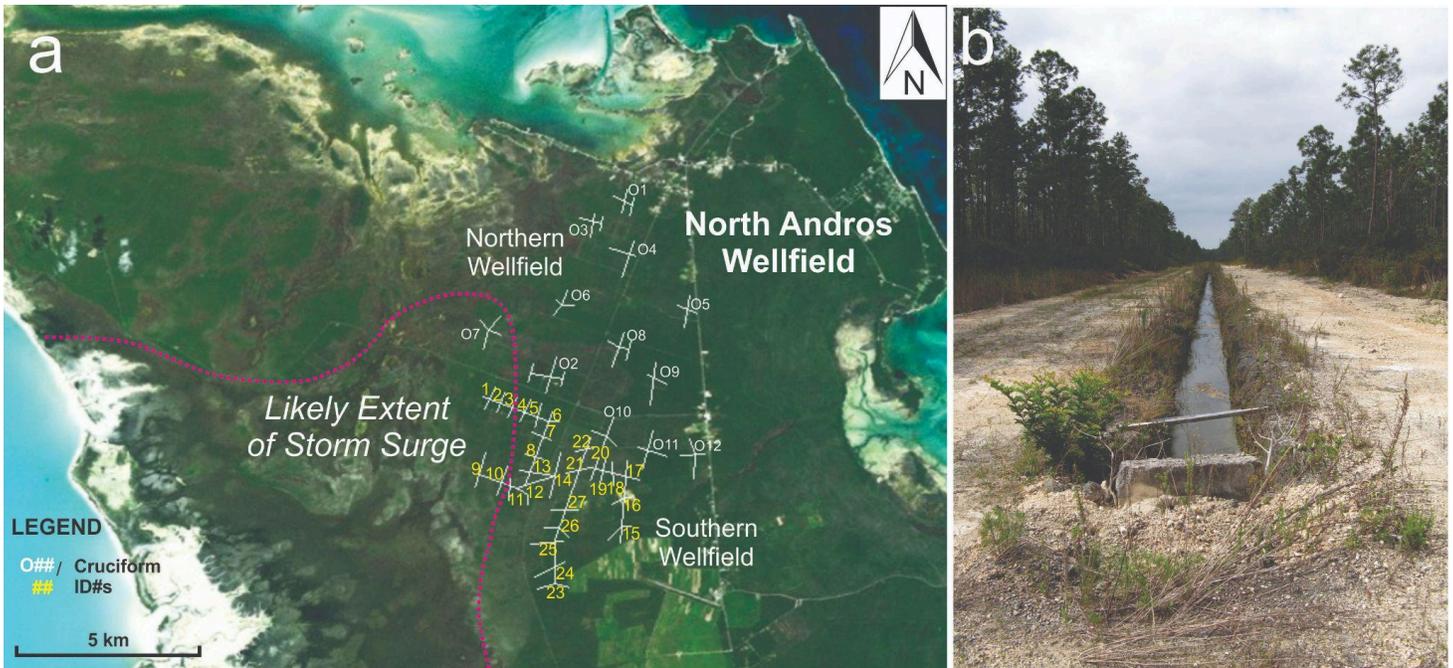
Figure 11. (a) Aerial view of the North Andros Wellfield showing the trench network. The likely extent of the storm surge in 2004 is shown. (b) A trench that skims fresh water from the top of the FWL, conveying the water to a central cruciform (forefront).

Water quality within the FWL is relatively steady throughout the year with little seasonal change in salt concentration between the wet and dry seasons. However, in September 2004, Hurricane Frances (Figure 12a) traveled across The Bahamas from the southeast to northwest (Franklin et al., 2006). The hurricane ranged from a Category 4 to Category 2 on the Saffir Simpson Hurricane Scale. The hurricane caused a storm surge on

the west coast of Andros Island that resulted in sea water overtopping the land surface and causing salinization of the North Andros Wellfield. The exact time of occurrence and the nature of the storm surge are unknown because the western coast of Andros Island is largely unpopulated, but it is assumed that the surge occurred between September 3-4, 2004, while Hurricane Frances passed near Andros. After the hurricane had passed, evidence of the storm surge was observed, such as the presence of marine fish at inland locations and flooded ground (Figure 12b and 12c). The likely extent of the storm surge (shown on Figure 11a) was based on observations of damage and evidence of flooding, which was observed to be up to 1 m deep. The saline water was pumped out of the trench network a few days after the storm, and water quality was largely returned to natural conditions. Groundwater modeling of the salinization of the FWL due to the storm surge indicated that pumping out the saline water from the trench improved the recovery time (Holding and Allen, 2015).
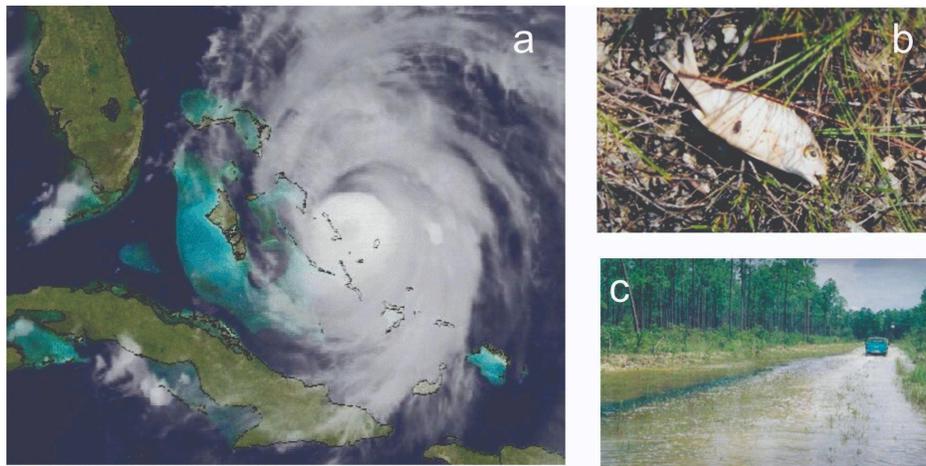
Figure 12. (a) Hurricane Frances over The Bahamas in September 2004. Evidence of the storm surge including (b) marine fish at inland locations and (c) flooded ground.

Protecting Freshwater Resources

Globally, freshwater resources on small islands are challenged by a number of stressors, including limited freshwater availability (i.e., thin FWLs), climate variations, sea level rise, extreme climate events, and population growth (White and Falkland, 2010; Holding and Allen, 2016; Post et al., 2018; Spellman et al., 2021). The FWLs on small islands are particularly at risk because they are small in extent and relatively thin, making them vulnerable to these stressors. Lens thinning increases the salinity of the water supply.

Salinity is the dissolved salt content of a body of water. Water that is saline contains significant amounts (referred to as "concentrations") of dissolved salts, the most common being sodium chloride (NaCl). Fresh water has a salinity of less than 1,000 milligrams of salt per liter of water (mg/L), while ocean water has a salinity of about 35,000 mg/L (United States Geological Survey (USGS), 2018). Salts can be toxic to freshwater plants and animals and can make water unsafe for drinking, irrigation and livestock watering (US Environmental Protection Agency (US EPA), 2022). Slightly saline water (e.g. having up to 2,500 ppm of salt) is sometimes used for irrigating crops (USGS, 2018). Normally, though, moderate to high saline water has limited uses. Salinity can be a chemical stressor in the aquatic environment as fluctuating levels of salinity can affect aquatic biological organisms which are adapted to prevailing salinity concentrations (US EPA, 2022).

A reduction in the areal extent and thickness of the FWL and the consequent salinization of the lens can occur for a variety of reasons, including sea level rise, changes to local climate conditions due to climate change, extreme weather events, and human intervention.

Sea Level Rise (SLR)

Mean sea level is projected to rise by approximately 0.65 m in The Bahamas by the 2070s (relative to 2008) under a realistic future global scenario (RCP8.5) (World Bank Group, 2021). As sea level rises, the boundary between the ocean and the land moves inland, causing a reduction in the lateral extent of the FWL. The water table will also rise if there is space to accommodate it (that is, if the land surface is high enough). In this case, there may be minimal impact on the lens thickness. This is generally the case for Andros with its relatively high topography. When there is no space to accommodate a rise in the water table, the FWL will reduce in size. This is the case for many low topography islands, such as most other islands in The Bahamas.

Change in Local Climate Conditions

The majority of precipitation in The Bahamas occurs during the rainy (wet) season from May to October (Little et al., 1973; Cant and Weech, 1986; Bukowski et al., 1999; Gamble and Jordan, 2006). The southern region of Andros receives less precipitation (889 mm/yr) than the northern region (1,442 mm/yr). Across the island, precipitation is lost primarily through evapotranspiration (Little et al., 1973); very little precipitation forms overland runoff or soil moisture storage due to the thin or absent soil zone, the high permeability of the limestone, and minimal paved areas (Tarbox, 1986). The remaining water constitutes the sole recharge to the aquifer. Recharge occurs throughout the year; however, increases in recharge rates are expected during the summer rainy season, when the majority of precipitation occurs. Holding (2014) estimated the historical average annual recharge to the aquifer on North Andros at 877 mm/year, ranging from 514 to 1,412 mm/yr depending on the variability of the climate (wetter in some years and drier in others).

While the climate, and thus the recharge, varies naturally, over the longer term, the geometry of the FWL remains relatively stable. However, climate change can alter the timing and amount of recharge. An increase in air temperature and shifting precipitation patterns are projected for The Bahamas, leading to an increase in evapotranspiration and a consequent reduction in recharge (Holding and Allen, 2016; Spellman et al., 2021). Holding (2014) estimated that the future (2080s) recharge on North Andros at 777 mm/year (an 11% decrease relative to historical recharge). Holding and Allen (2016) estimated that the reduction in recharge, coupled with the rise in sea level, would result in the FWL reducing in areal extent by ~4% and in volume by ~6% under future climate change conditions. The majority of the reduction in areal extent and volume of the FWL on Andros are caused by a reduction in recharge, rather than by SLR, and the impacts are most notable along the coastline where the freshwater-saltwater interface moves inland.

The FWL on Andros Island, overall, is relatively resilient to the effects of climate change. This means that the fresh groundwater supply on Andros will be a viable freshwater resource into the future unless other significant stressors come into play.

Extreme Weather Events

Climate change is also associated with the occurrence of extreme weather events, such as hurricanes. The Bahamas is situated within the Atlantic Hurricane Belt, an area that is prone to hurricanes, which occur predominantly between June 1st and November 30th (National Hurricane Center, National Oceanic and Atmospheric Administration (NOAA), 2014). Some studies suggest that the frequency and intensity of hurricanes will increase under a warmer climate, but trends are uncertain (Knutson et al., 2010).

Such extreme events can lead to coastal erosion, which reduces the land area available to support a FWL. Storm surges, as discussed above in relation to Hurricane Frances, and tidal action can amplify the impacts of salinization of the FWL. Holding and Allen (2016) found that the FWL on Andros is generally able to recover from storm surge inundation over time as fresh recharge flushes the salt plume out of the aquifer. Eventually, the FWL returns to the original geometry.

Human Interventions

Land excavations related to canals and open pit mines are human interventions that can result in significant impacts to a FWL on an island and in coastal aquifers. When an open pit penetrates an aquifer, significant amounts of groundwater flows to the pit. Therefore, the large volumes of water must be pumped to provide a dry mining condition. On an island, there is an additional problem. When the land is excavated, the saline groundwater moves vertically upward under the excavation; this is referred to as upconing.

Holding (2014) used the groundwater model for Andros to model the upconing effect due to excavations on North Andros for limestone quarrying. Recharge to the FWL was assumed to be unaffected by climate change. A network of pumping wells was added to the groundwater model to simulate the dewatering associated with the two proposed open pits on Andros (Figure 13). The pumping wells are screened to a depth of -25 m and each pump at a rate of 20,000 m^3 per day for 10 years to lower the water table in the excavations. Figure 14 shows the modeling results. The top image shows the salinity distribution on North Andros; the dark blue shading shows the lateral extent of the FWL. The FWL is highly impacted by the quarries.The lower figure shows a vertical cross section along the line shown in the top figure. Here, the effect of the quarries is to cause significant upconing of the saline groundwater under the quarries.

The presence of large open surface mining pits will further amplify salinization risk during storm surge events. The water would not be able to be pumped out, leaving saline water in the pit that could contaminate the freshwater surrounding the pit. Additionally, the proposed completion phase of the project intends to allow mining pits to fill in as 'lakes', likely with high salinity water. Because the proposed pits are in proximity to the ocean, sea-level rise, wave events, and storm surges will accelerate and perpetuate mining-induced salinization, even after mining has ceased. The exposed surface water pits/'lakes' will act as open conduits for vertical saltwater intrusion without the added protection of surface soils. As a result, mining impacts could lead to chronic salinization with lasting effects on nearby ecosystems long after mining has stopped.

The FWL on Andros should be protected to avoid a significant loss of freshwater resources due to mining operations that will lead to salinization due to upward vertical migration of the saline water beneath and surrounding the quarries.

Figure 13. Proposed limestone quarries (5000 acres and 1000 acres) on North Andros.
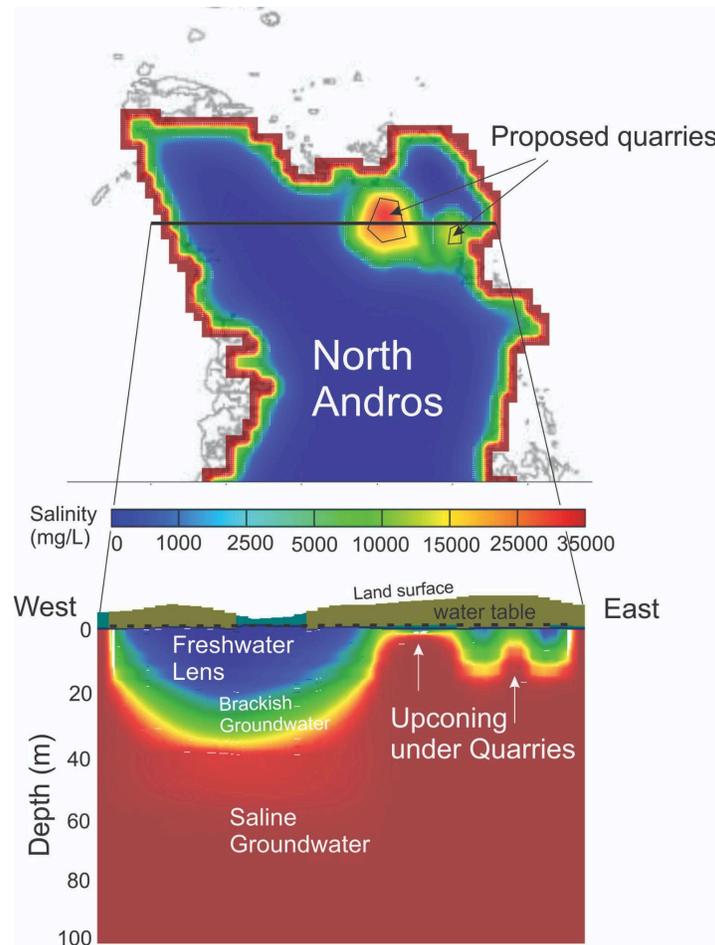
Figure 14. Groundwater model output for two proposed quarries situated at the northern end of the island. (Top Figure) Map of the salinity distribution on North Andros showing the lateral extent of the freshwater lens (dark blue) and how it is impacted by the quarries. (Bottom Figure) A vertical cross section along the line shown in the top figure. Here, the effect of the quarries is to cause significant upconing of the saline groundwater under the quarries.

Protecting Water Quality

In coastal and island aquifers, like North Andros, groundwater quality can depend on complex interactions between freshwater and saltwater. Physical processes, like tides and waves, can oscillate the location of the freshwater-saltwater mixing zone with associated changes in water quality (Moore, 1999). Such episodic oscillations are a natural feature of many coastal aquifers and help to explain why they are termed 'natural biogeochemical reactors' (Santos et al., 2011). However, changes in salinity from mining-driven salinization of the freshwater lens could lead to chronic water quality alterations that eclipse many of these natural features of coastal aquifers. Because the proposed mine will require groundwater pumping that drives vertical migration (upconing) of the saltwater layer, the most obvious threat to fresh groundwater quality from mining is salinization.

Maintaining adequate groundwater quality on Andros is important to retaining drinking, irrigation, and ecosystem uses (termed 'designated uses'). In many regions globally, water quality standards have wide-ranging guidelines that are specific to designated uses for protection against activities that degrade water quality (US EPA, 2017). For instance, saltwater could be used for recreation but would not be suitable for consumption. Salinization of the freshwater lens will degrade drinking, irrigation, and ecosystem uses. Drinking water standards often require salt concentrations below 500 mg/L (EPA, 2023), and irrigation water generally needs to remain below ~1000 mg/L to avoid salt accumulation and toxicity in plants, though even much lower concentrations of individual ions, like chloride or sodium, can be harmful to certain crops (Bauder et al., 2011). Model results of salinization from mining on North Andros show fresh groundwater salt concentrations could increase to nearly 35,000 mg/L, close to values of pure seawater (see Figure 14). The spatial extent of salinity increases associated with mining can also be substantial. In Florida, where open pit limestone mining is relatively common, models suggest that salt contamination can reach over 1 km laterally from pit locations and may persist for over 70 years (Naja et al., 2010).

Changes in salinity will subsequently alter other aspects of groundwater quality. Increases in the salinity of groundwater can impact concentrations of macro-nutrients, like nitrogen and phosphorous, and micro-nutrients, like iron and manganese, via changes in chemistry that facilitate the release and/or sorption of various elements in coastal aquifers (Moore and Joye, 2021). Such nutrients, at low concentrations, are critical for biological function, but, at higher concentrations, can be harmful. Alterations in salinity can likewise shift the microbial community composition of coastal aquifers as bacterial assemblages can be highly adapted to specific salinity ranges, with similar impacts on nutrients (Archana et al., 2021). Such alterations in bacterial groups could trigger changes in groundwater nutrient chemistry as some bacteria are more active at higher salinities (Ruiz-González, 2022).

Much of the salinity in saltwater arises from dissolved minerals that accrued from the erosion of rocks on land, leading saltwater to consist of higher concentrations of oxygen-containing dissolved minerals, like sulphate, relative to freshwater. The increased abundance of sulphate associated with higher salinity water can be an important control on biological processes in coastal aquifers that affects water quality (Moore and Joye, 2021). In freshwater, the low abundance of oxygen-containing dissolved species often acts as a limit to biological/chemical processes as many metabolic processes rely on oxygen. Changes to biological processes from increased availability of oxygen in coastal aquifers can have implications for water quality as microbes

consume/produce nutrients. Like salt, nutrients can impair designated uses and further alter biological and chemical processes in aquifers.

Mining can also generate and introduce entirely new classes of water contaminants during site preparation, extraction, and processing phases. Potential pollutants associated with limestone mining operations include limestone dust as well as oil and gas from machinery. In limestone mining operations, crushed rock is commonly produced via ammonium nitrate fuel oil (ANFO) explosives (Naja et al., 2010). ANFO used for limestone mining in the Lake Belt Region of Florida is suspected to have caused benzene contamination nearly five times the legal limit of 1 part per billion in a critical drinking water aquifer (*see* https://protectnepa.org/florida-lake-belt/). Because ANFO combustion is often incomplete, use of explosives during mining can also leave behind highly soluble waste products, like nitrogen-based nutrients (Brochu, 2010). Other impacts from use of ANFO include fuel oil contamination of groundwater (Brochu, 2010).

More generally, environmental mandates in places like the United States commonly find industrial mining waste discharge impacts water turbidity, dissolved and suspended solute concentrations, and pH (FSS, 2023). These pollutants can travel into both surface and groundwater sources and alter their chemical properties. Several studies in India found that limestone mining operations resulted in increased alkalinity, electrical conductivity, total dissolved solids, hardness, and calcium and sulphate concentrations in water at and around the mining site (Bhatnagar et al., 2014; Lamare and Singh, 2014). This degradation of water quality in the area greatly reduced potable and irrigation water availability, which exacerbated water scarcity issues and limited agricultural opportunities. In a karst environment, contaminated water can travel especially quickly through fractures and spaces in the rock to areas well beyond the mine site. This can have detrimental impacts to both humans and wildlife in surrounding areas (Figure 15).
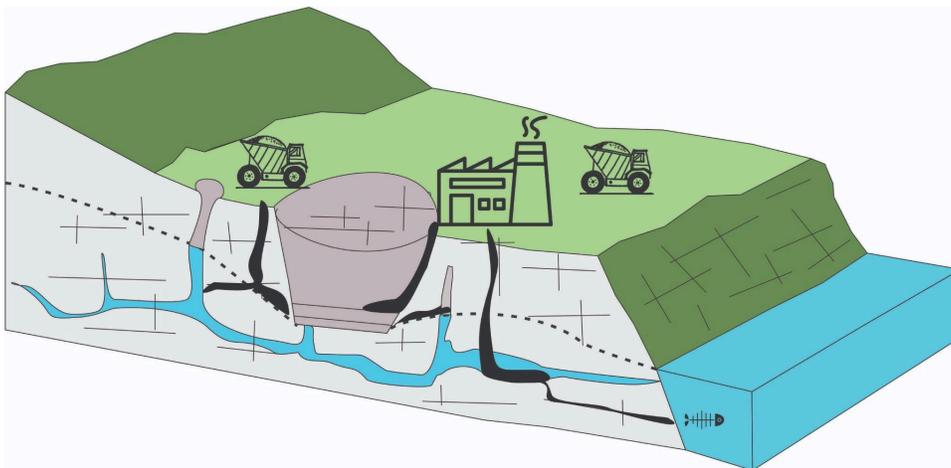
Figure 15. Contamination of karstic limestone from mining operations.

Open surface pits from mining also render underlying groundwater more susceptible to surface contamination. In Florida, surface mining pits were associated with an increased risk of transport of disease-causing organisms, like *Giardia* and *Cryptosporidium* (*see* Sierra Club v. Flowers, 423 F. Supp. 2d 1273). Mining-generated dust and surface water run-off, both of which could contain diverse nutrients/water contaminants, may also penetrate groundwater supplies more readily in the presence of large surface excavation pits that allow for

accumulation and infiltration/deeper recharge without the protection of surface soils. Additionally, long-term plans include permanent establishment of the pits as lakes. This transition from drained surface pits to filled-in lakes could further increase bacterial and nutrient contamination from surface water run-off and wildlife use of the area.

Accumulating Future Impacts on Water Quality in the Face of Climate Change

Potential changes in water quality are also important to consider in line with climate change impacts. In the case of North Andros, the recovery time of the freshwater lens is threatened by accumulating salinity stresses from both mining-induced salinization and co-occurring climate change impacts. With climate change, reductions in freshwater recharge are likely as declines in mean annual rainfall are expected in the Caribbean (IPCC, 2021), which will likely amplify the salinization effect, and may also lead to slower flushing times of contaminants.

On the marine side, climate change impacts, like sea level rise or coastal flooding, will also impact the recovery of the freshwater lens from salinization. Progressive storm events, coastal flooding, and sea level rise will amplify mining induced salinization to create accumulating salinity stresses as saltwater will likely be unable to be fully flushed before the next storm/flooding event (Nordio et al., 2023, Storlazzi et al., 2018). Past work shows fresh groundwater recovery times from marine climate change impacts alone can vary widely, from years (Post et al., 2017) to decades (Yang et al., 2013). Because recovery of the freshwater lens could persist indefinitely in the face of climate change, the cascading impacts of other salinity-dependent biological/chemical shifts may very well persist on this time scale too.

Preserving Natural Water Features

One unique landform created as a result of karst processes are blue holes. Blue holes are important ecosystems in North Andros and home to diverse and unique fauna (Bishop et al., 2015; Gonzalez et-al., 2011). Blue holes, which are globally uncommon ecosystems, hold important value for the community and are abundant (>175) throughout Andros, with depths commonly exceeding 100 m (Juberthie and Iliffe, 1994). Blue holes have value for tourism and local recreation. The Blue Holes National Park contains over 20 blue holes. Many companies also rely on tourism associated with blue holes throughout Andros. Ecosystem services, including those associated with blue holes, contribute to an estimated net economic benefit of $260 million a year on Andros (Hargreaves-Allen, 2010).

Species found in these subterranean ecosystems can be highly endemic, meaning they are found in only 1-2 locations globally (Calderón-Gutiérrez et al., 2018). Specific to the blue holes of the Bahamas, new classes of crustaceans, remipede (blind crustaceans), over 40 new species of stygobites have been found (Juberthie and Iliffe, 1994). On Andros, new species identified span the classes of remipede (blind crustaceans), amphipoda, ostracoda (seed shrimp), *thermosbaenacea* (cave microshrimp), and *cumacea* (hooded shrimp) (Juberthie and Iliffe, 1994). These biota evolved to the unique physical and chemical conditions of blue holes, which formed over long periods of time (Mylroie et al., 1995). Some blue holes initiated via extensive fracturing that likely began during formation of the Bahamas platform over 100 million years ago (Whitaker and Smart, 1997). Others likely arose simply by dissolution of carbonate during global sea level changes (Mylroie et al., 1995).

The ecology of and ecosystem services provided by blue holes are threatened by changes to freshwater quality and quantity induced by mining. The proposed mining pits are immediately adjacent to at least one well-known and frequented blue hole, Uncle Charlie's Blue Hole (Figure 16), which is just over 2000 m from the proposed mining pits. As systems directly connected to and supported by groundwater, salinization of the freshwater lens from mining would render inland blue holes proximal to the mining pits at risk of similar salinity impacts. Salinity gradients often exist in inland blue holes in The Bahamas, where freshwater surface layers overlay deeper saltwater (Gonzalez et al., 2011), reflecting the salinity structure of the surrounding aquifer.

Figure 16. Uncle Charlie's Blue Hole, North Andros, Bahamas. Credit: Diana Allen.

Because inland blue holes on Andros often have freshwater surface layers (Gonzalez et al., 2011), changes in the salinity and general water quality of the freshwater lens would also likely impact the ecology of these systems. Blue hole biota are commonly adapted to specific areas of the water column as salinity, nutrient, and oxygen content can vary with depth in the inland, vertically stratified blue holes of Andros (Figure 17). These depth-dependent chemical profiles are known to influence zooplankton community ecology (Kornicker et al., 2002) and microbial ecology (Gonzalez et al., 2011). Past work suggests that even slight changes to organic matter inputs and water flow could have large impacts on blue hole ecology in The Bahamas (Gonzalez et al., 2011). Other additional changes to water quality from the mine that affect the turbidity of surface water runoff could also contribute to increased loadings of suspended sediment to blue holes that impact light availability at the surface. Light availability is critical to supporting photosynthetic organisms in the surface layers of blue holes.
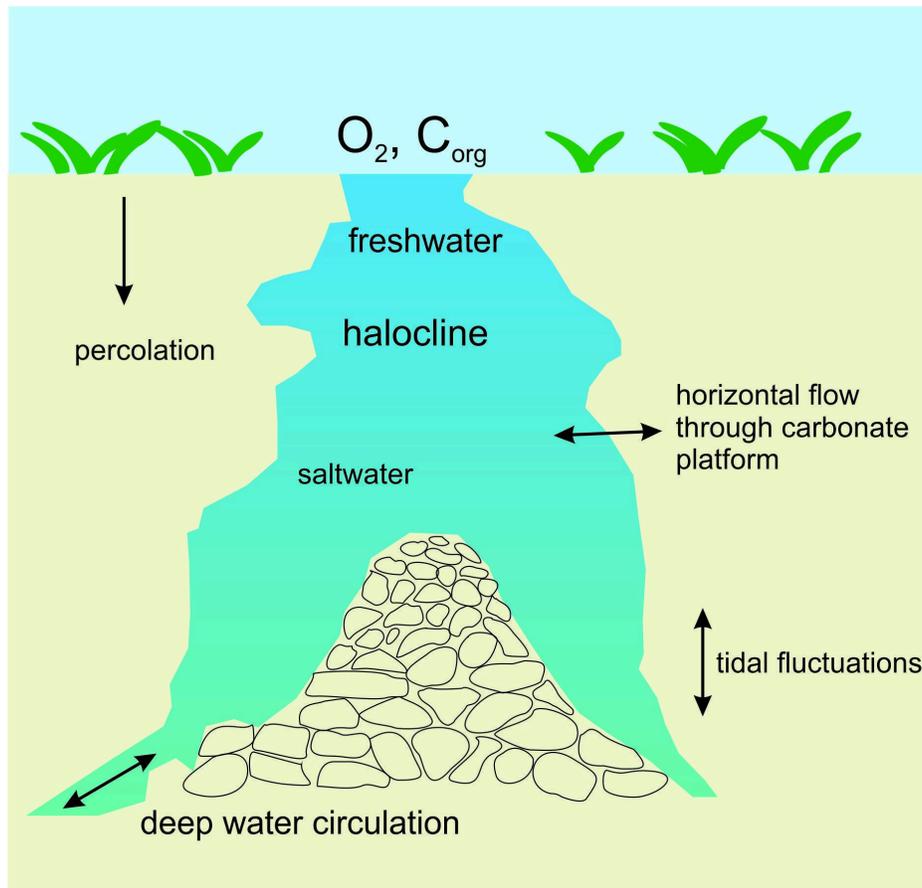
Figure 17. Inland blue hole showing a salinity gradient, where a freshwater surface layer overlays deeper saltwater. Modified from Gonzalez et al. (2011).

	# The Terrestrial Environment

Terrestrial Habitats

North Andros is home to extensive forest cover that is crucial habitat for flora and fauna. Andros harbors rich biodiversity, providing habitat for numerous endemic bird, reptile, and other vertebrate species (Antalffy et al., 2021). Andros' terrestrial landscape is characterized by habitats comprising Caribbean pine, broadleaf coppice, woody shrubland, grassy shrubland, agriculture, and developed land (Figure 18). These forests provide important ecological services, like carbon sequestration, supporting biodiversity, and have economically benefited Andros through commercial logging (Antalffy et al., 2021; Curtis et al., 2018).
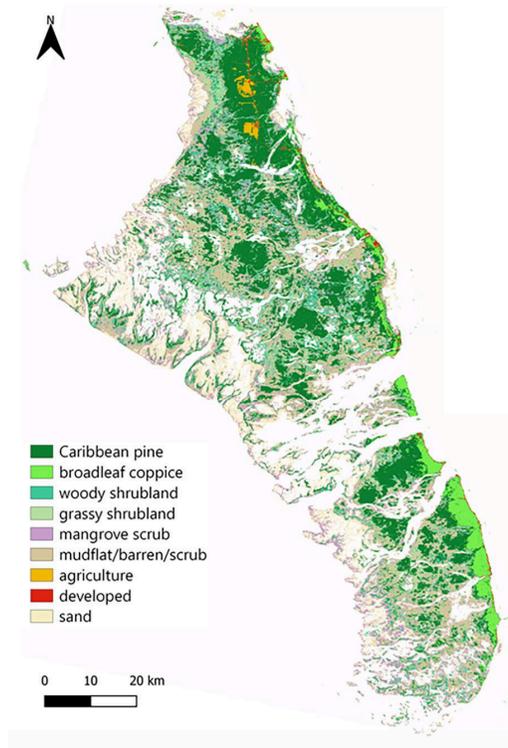
Figure 18. Land cover classification map of nine major terrestrial habitats on Andros. Image Credit: Antalffy et al. (2021).

The Northern region of Andros is dominated by the Caribbean Pine, *Pinus caribaea,* covering 31% of the total land (Table 1). Within the Bahama Archipelago, Caribbean Pine makes up the most extensive land cover on Andros and likely represents the largest remaining pine rockland habitat worldwide (Antalffy et al., 2021). These pines are vital habitats for endangered and wintering birds such as the Bahama Oriole, Great Lizard Cuckoo, Key West Quail Dove, and piping plovers. Because of this, the Bahamas Archipelago is classified as a global diversity hotspot, an Important Bird Area (IBA), and an Endemic Bird Area (EBA; Stattersfield et al., 1998; Currie, 2005; Myers et al., 2000).

Table 1. Total area and percent of terrestrial habitat classes, descending from largest to smallest (total land area). Image Credits: Antalffy et al. (2021).

Class	North Andros	
	km²	% Total
Caribbean pine	1,073	30
Mudflat/barren/scrub	708	21
Sand	441	13
Mangrove scrub	364	11
Woody shrubland	367	11
Grassy shrubland	304	9
Broadleaf coppice	106	3
Agriculture/secondary	27	1
Developed	18	1
Total	3,407	100

The presence of mining operations poses substantial risks to the survival of endemic and endangered bird species and other fauna in North Andros. This is primarily due to habitat destruction and its adverse effects on animal behavior and health. The loss of these birds is not only ecologically detrimental but also threatens the Bahamian Gross Domestic Product (GDP) which relies heavily on birding tourism. Tourism is the main fiscal driver of The Bahamas, contributing to almost 40% of the country's GDP (Figure 19). In 2014, ecotourism from bird watchers brought in an estimated $39 million to The Bahamas (USD; Lipp, Center for Responsible Travel). Moving forward with the proposed mine could endanger essential bird species and their habitats with subsequent impacts to the economy.

Figure 19. Tourism Statistics for The Bahamas. Image Credits: Center for Responsible Travel.

Vulnerable Terrestrial Species

Endangered and Endemic Species

North Andros is home to many endemic and endangered bird species. Over 300 species have been documented within the archipelago, with over 200 birds being frequent inhabitants, and 109 breeding species (i.e., birds that actively participate in reproductive activities, such as building nests or laying eggs, on Andros). Of the breeding species, three are endemic to the region and 34 are endemic subspecies (Currie et al., 2005). Within the Bahamas Archipelago, 17 (50%) of the subspecies native to the Bahamas reside on Andros (Antalffy et al., 2021). These endemic and endangered species are range-restricted making them inherently more vulnerable to extinction and require more focused habitat management and conservation to protect their limited distribution and small populations.

One important species is the critically endangered Bahama Oriole, *Icterus northropi* (Figure 20). This bird species, once found on Abaco and Andros, now lives solely on Andros (Stonko et al., 2018; Rowley et al., 2021; Antalffy et al., 2021). The restricted global population of the Bahama Oriole had previous estimates suggesting a population size of fewer than 300 individuals (Rowley et al., 2021). A recent study, however, found the population to be higher but still emphasizes the need to conserve their habitat (Rowley et al., 2021). The Caribbean Pine that dominates North Andros is found to be the main habitat of the endangered Bahama Oriole (Antalffy et al., 2021). The proposed mine plans to remove these birds' sole habitat thus placing them at risk of extinction.

Figure 20: The critically endangered Bahama Oriole is found only on Andros, Bahamas. Photo: Steve Brezinski

Wintering Birds

Andros serves as a crucial wintering ground for numerous bird species. In the Bahamas, Neotropical and Nearctic migrants compromise up to 50% of terrestrial bird species during the winter (Wunderle and Waide, 1993; Lee, 1996; Currie, 2005). The Kirtland's Warbler, *Setophaga kirtlandii*, a rare species with only 600 individuals remaining, winters exclusively on Andros. The endangered migratory Atlantic subspecies of the Piping Plover, *Charadtius melodus*, also spends two-thirds of its year wintering on Andros (Figure 21). Previous threats of habitat destruction from proposed mining activities led to the creation of the Joulter Cays National Park, an area that hosts 10% of the Atlantic Coast Piping Plover population, along with many other sea- and shorebird species (National Audubon Society, 2020). Although Joulter Cays is now a designated national park, the highest density and diversity of wintering birds were found in the pine habitat of Andros, emphasizing the importance of preserving these forests from future mining activities.

Figure 21: Piping Plovers in Joulter Cays in the Bahamas. Photo: Walker Golder

The Bahamian Andros Iguana

The Bahamian Andros iguana (*Cyclura cychlura cychlura*) is the largest native terrestrial vertebrate in the Bahamas. The Andros iguana is the only iguana in the world known to deposit its eggs in termite mounds and the only species of iguana in the Bahamas that is not restricted to small cays (Knapp, 2005). It is estimated that approximately 3,500 iguanas remain on the island (Knapp and Buckner, 2004) but estimates are in desperate need of updating. Studies suggest that the Andros iguana selects pine woodland with open broadleaf understory as its primary habitat and impacts from historic large-scale logging practices for Caribbean pine (*Pinus caribaea*) destroyed large tracts of iguana habitat in the 1960s and 70s (Little et al., 1976; Knapp et al., 1999). As a result of this and other anthropogenic stressors, the Andros iguana is protected by Bahamian Law and listed as Endangered according to International Union for the Conservation of Nature (IUCN) Red List criteria, but their numbers have failed to increase (Knapp and Buckner, 2004).

Habitat Disturbance and Destruction

Habitat Removal

Mining operations will result in complete habitat removal, threatening the many endangered and endemic species of Andros. For several of these species, the threats from mining would exacerbate existing threats to habitat such as expansion of agriculture, rapid industrialization, and climate change (Saha and Padhy, 2011). Increased deforestation and forest fragmentation may have significant impacts on local biodiversity and species composition. It remains unclear how most forest species will react to changes in habitat extent and distribution; however, studies suggest that even small levels of deforestation and fragmentation are linked to higher extinction risks and reduced biodiversity (Betts et al., 2017; Antalffy et al., 2021).

The proposed mine will create two large quarries, 1,000 acres, and 5,000 acres, on the northern side of the island (Figure 13). Mining operations would require permanent landscape change, most notably deforestation. North Andros is predominantly covered by about 1,073 km^2 of Caribbean Pine, (Antalffy et al., 2021), which serves as crucial habitat for many endemic, wintering, and endangered bird species. Overall, deforestation is the largest threat to these economical and ecologically valued bird species, as well as other important fauna.

Noise Pollution

Open-cast mining produces noise pollution through exploratory and production drilling, blasting, cutting, handling of materials, ventilation, crushing, conveying, ore processing, and transportation (Donoghue, 2004). Studies have shown that this noise negatively impacts species diversity and richness, population density, distribution, and reproduction (Saha and Padhy, 2011; Duarte et al., 2015). Bird populations in forests adjacent to mining operations have lower species richness and abundance compared to populations farther from the mine (Saha and Padhy, 2011; Duarte et al., 2015) (Figure 22). Noise pollution also impacts bird communication, which is especially important for mating and reproduction. Loud environments interfere with communication and reduce the pairing success of birds by almost 15% (Goudarzi, 2006).
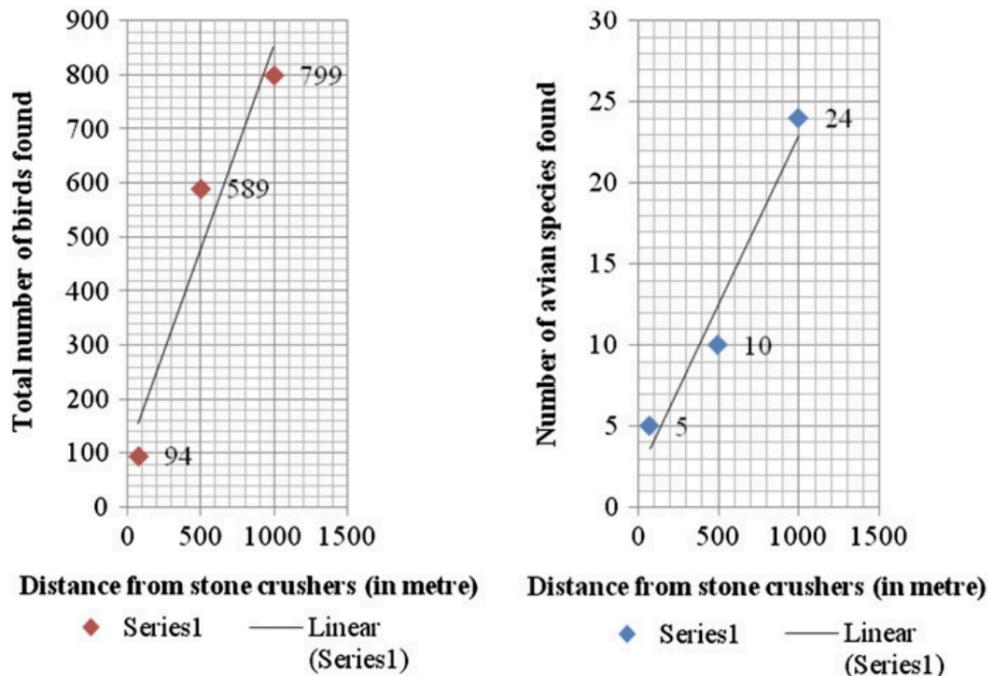
Figure 22. Graphical representation of the increase in abundance (left) and species richness (right) of birds with an increase in distance from the source of pollution (stone crushers) at Lalpahari forest. Image Credit: Saha and Padhy (2011).

Air Pollution

Mining processes, like the crushing of stones, result in air pollution of small particulates, like dust. This air pollution can remain in the air and may be transported to surrounding forest ecosystems where it may have adverse effects on flora and fauna (Saha and Padhy, 2011). The effects of air pollution from mines on human health are well studied, impacting both the respiratory and cardiovascular systems (Donoghue, 2004). Therefore, it is expected that fauna near mining sites will also experience adverse health effects. Studies have found that exposure to air pollution impacts hematological and biochemical parameters, weight, breeding success, eggshell quality, and overall survival (Sahad and Padhy, 2011; Eeva and Lehikoinen, 1994).

Forest Health

The Forest

Andros is a heavily forested island that supports rich biodiversity and provides valuable ecosystem services. North Andros contained one of the largest virgin stands of open pine habitat in the West Indian region until it was impacted by large scale, government-subsidized land clearing for agriculture and logging and other human activities (Eshbaugh and Wilson, 1996). North Andros is dominated by Caribbean Pine, *Pinus caribaea* (Figure 18). Caribbean Pine makes up the most extensive land cover class on Andros and constitutes the world's largest areas of remaining pine rockland habitat (Antalffy et al., 2021). This species is unique, and studies call for these pines to be of high conservation priority (Antalffy et al., 2021).

Forests provide vital ecological services, such as combatting the effects of climate change and supporting biodiversity (Antalffy et al., 2021). The proposed North Andros mine will cause significant impacts to forest health which could devastate biodiversity and the essential ecosystem services provided by the island's forests.

<u>Deforestation</u>

Deforestation is happening at an exponential rate due to anthropogenic activity and globally, mining is one of its top drivers (Radwin, 2023). The proposed mine on North Andros will result in large-scale deforestation of vital terrestrial habitats. During mining, deforestation occurs when the trees, vegetation, and soil are cleared to expose the limestone bedrock. The removal of plants and trees for mineral exploitation causes major land degradation, which significantly impacts local ecosystems (Sudhakar et al., 2022). Deforestation devastates numerous plant and animal habitats, resulting in significant biodiversity loss. This loss of forest habitat has negative impacts on biodiversity not only on co-located habitats but beyond the mine site as well (Arbogast et al., 2000; Ganapathi and Phukan, 2020; Wang et al., 2012).

Forests are essential in combating climate change, acting as powerful carbon sinks by absorbing and storing carbon dioxide from the atmosphere. Forests sequester approximately 20% of annual global CO_2 emissions (Harris et al., 2021). When forests are cleared, this stored carbon is released back into the atmosphere, which contributes to climate change rather than combating it (Sedjo and Sohngen, 2012).

<u>Salinization</u>

Mining operations can lead to soil becoming more vulnerable to erosion and saltwater intrusion, which can cause groundwater salinization (Selvakumar and Chandrasekar, 2021) and potentially lead to the formation of "ghost forests". Ghost forests occur due to saltwater inundation from rising sea levels and coastal flooding, transforming once-thriving forests into vast graveyards of dead trees that can no longer support existing terrestrial biodiversity.

In addition to salinization from mining, climate change can also drive further salinization. Although salinization has naturally occurred from seasonal hurricanes, its prevalence is projected to escalate due to rising sea levels and the heightened frequency and intensity of storms (Antalffy et al., 2021). Recent hurricanes and tropical storms decimated entire swaths of pine forest on the islands of Andros, Abaco, and Grand Bahama, making these areas even more vulnerable and sensitive to the potential threats of mining operations (Antalffy et al., 2021) (Figure 23).

Figure 23. Image of dead Caribbean Pines as a result of saltwater inundation from storm surges. Image Credits: Currie et al. (2019).

Sediment and Dust Pollution

Mining activities generate dust and sediment pollution, leading to widespread forest degradation. Air pollution from limestone mining is caused by drilling, blasting, loading, transportation, unloading, and crushing operations that introduce dust particles into the air (Sudhakar et al., 2022). A study comparing forest sites with no dust accumulation relative to sites with heavy dust accumulation found significant differences in composition and structure. The dust site had reduced density of woody stamps, seedlings, shrubs, saplings, and dress leading to significant changes in forest community structure and composition (Brandt and Rhoades, 1972).

Soil Health

In mined areas, the soil is affected by various mining operations including blasting, drilling and storage of overburden dump materials, clearing of land, construction of ancillary facilities, and movement of vehicles (Sharma et al., 2013). Some of the negative consequences related to soil health identified from limestone transportation and processing include the loss of vegetation cover and land degradation by the dumping of overburdens/spoils and lime waste material, mass destruction of water bodies due to dumps encroachment, loss of biodiversity, and land-use changes (Sudhakar et al., 2022).

Topsoil Removal

The proposed mine will require completely removing and destroying topsoil from the entire project area. Topsoil is the most fertile component of the soil structure and takes thousands of years to form. The removal of topsoil is difficult to reclaim, and the loss of this fertile and productive soil can be irreversible (Ganapathi and Phukan, 2020). Topsoil is removed using excavators and dumpers, resulting in soil erosion (Sudhakar et al., 2022)

(Figure 24). Removed or deteriorated fertile topsoil can inhibit tree and vegetation growth (Ganapathi and Phukan, 2020).
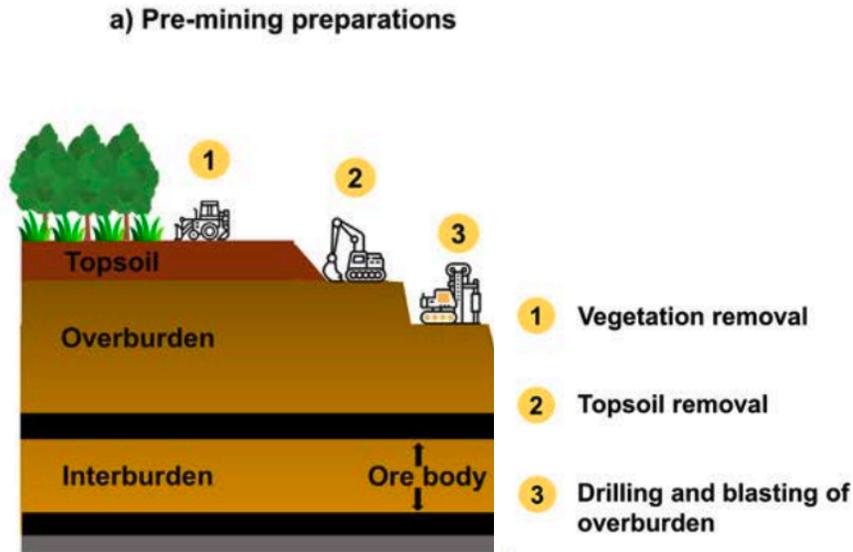

Figure 24. Phases of pre-mining preparation phase of a surface mine (modified from Gunathunga et al., 2023).

Soils are also vital carbon sinks that sequester and hold carbon. It is estimated that nearly 80% of the total carbon stored globally in terrestrial ecosystems is found in soil (Lal, 2004; 2008). Carbon is stored in soils in two ways that involve photosynthesis: humification and microphotosynthesis. Humification is the process where organic matter, such as plant material, decomposes and transforms into humus. Humus is a stable component of soil that stores carbon. Microphotosyntheis involves photosynthetic bacteria that live within the soil and sequester carbon (Sedjo and Sohngen, 2012). When this topsoil is removed during mining operations, this stored carbon is released back into the atmosphere as carbon dioxide.

Soil Quality

Limestone mining adversely affects soil quality by degrading its physical, chemical, and biological properties. Soil quality is "the capacity of a certain kind of soil to function with its surroundings, sustain plant and animal productivity, maintain or enhance soil, water, and air quality, and support human health and habitation" (Thakur et al., 2022). Soil quality plays a critical role in recovering an ecosystem (Sudhakar et al., 2022). Open-pit mining removes the topsoil and vegetation to extract the desired material. In addition to removal, mining operations often deposit waste substances onto the soil, further degrading soil quality (Lamare and Singh, 2016). These contaminants can be toxic to plants and microorganisms, disrupting soil ecosystems and reducing soil productivity. In a 2016 study by Lamare and Singh comparing soil quality in a limestone mining area with that of an unmined area, the soil quality in the mined area had degraded. The soil in the mining area was characterized by a decrease in moisture content, water-holding capacity, organic carbon, and total nitrogen (Lamare and Singh, 2016). These characteristics are crucial for productivity and structure to support terrestrial ecosystems. The removal and/or degradation of topsoil cannot be easily remedied even with rigorous methods of land reclamation (Sharma and Ram, 2014).

The Coastal Environment

Maintaining Critical Habitats and Biodiversity

<u>Habitats</u>

North Andros is home to many coastal environments including wetlands, shallow flats, and reefs (Figure 25). These environments contain habitats for ecologically, culturally, and economically valuable species. Proposed mining infrastructure and operations would have direct (e.g., clearing of mangroves, modification of estuaries/wetlands, dredging of seafloor populated by coral and/or seagrass) and indirect (e.g., increased sedimentation, beach loss) impacts on critical habitats. As seen elsewhere across the globe, this habitat alteration and degradation would result in a tremendous loss of biodiversity and ecosystem services (Naeem et al., 1994; Vitousek et al., 1997; Chapin et al., 1998).

North Andros wetlands and their habitats (i.e., tidal creeks, mangrove forests, seagrass) serve as nurseries, foraging, and nesting sites for migrating and resident wildlife (Valentine-Rose and Layman 2011). They support incredibly diverse fish and invertebrate communities by providing food, shelter, and protection from predators (e.g., Odum and Heald, 1972; Nagelkerken et al., 2000a). Seagrass beds and tidal creeks support the bonefish recreational fishery, which is thought to contribute millions of dollars annually to the Bahamian economy (Bahamas Ministry of Tourism, 2007).

Algal plains and seagrass beds, seaward of wetlands, and shoreward of the reef support a variety of ecologically and economically important species. The plains and seagrass serve as nursery habitats for Spiny lobsters (Arkema et al., 2017) and many coral reef fish (Robblee and Zieman, 1984; Arrivillaga and Baltz, 1999). The plains are also lifelong habitats for Queen Conch (Lobatus gigas), a fishery that generates over $76 million of annual revenue for the Bahamas (Sherman et al., 2018).

Further offshore is Andros' 220 km long barrier reef, which makes up 14% of all reef environments in the Caribbean (Burke and Maidens, 2004) and is the third-longest barrier reef in the world. High live coral coverage (20-54%) supports many culturally and economically valuable species, such as the Caribbean spiny lobster (*Panulirus argus*) and Nassau grouper. Though commercial fishing and expanded tourism led to the relative collapse of both fisheries (Ehrhardt and Deleveaux, 2007; Silvy et al., 2017), their annual landings are still worth over $1.67 million (Sherman et al., 2018). Other economically valuable reef fisheries include snappers (*Lutjanidae*), stone crab (*Menippe mercenaria*), jacks (*Carangidae*), grunts (*Haemulidae*), hogfish, and other groupers (*Epinephelidae*); cumulatively worth over $123 million annually (BDF, 1986; FAO, 2009; Sherman et al., 2018). In addition to supporting some of the most biodiverse ecosystems on the planet, they contribute to

tourism and recreation. Reef-associated tourism generates over $500 million in visitor expenditures, approximately 18.5% of Bahama's total tourist expenditures and 6.3% of GDP (Spalding et al., 2017). Andros' reefs also have tremendous conservation value as critical mating areas for nurse sharks, a nursery area for lemon sharks, and a refuge for bull sharks (The Nature Conservancy, 2006; Hargreaves-Allen, 2010). Rare, endangered, and charismatic species, such as the Kirtland's warbler, flamingos, and five of the world's seven sea turtle species, also frequent these pristine waters (Hargreaves-Allen, 2010).
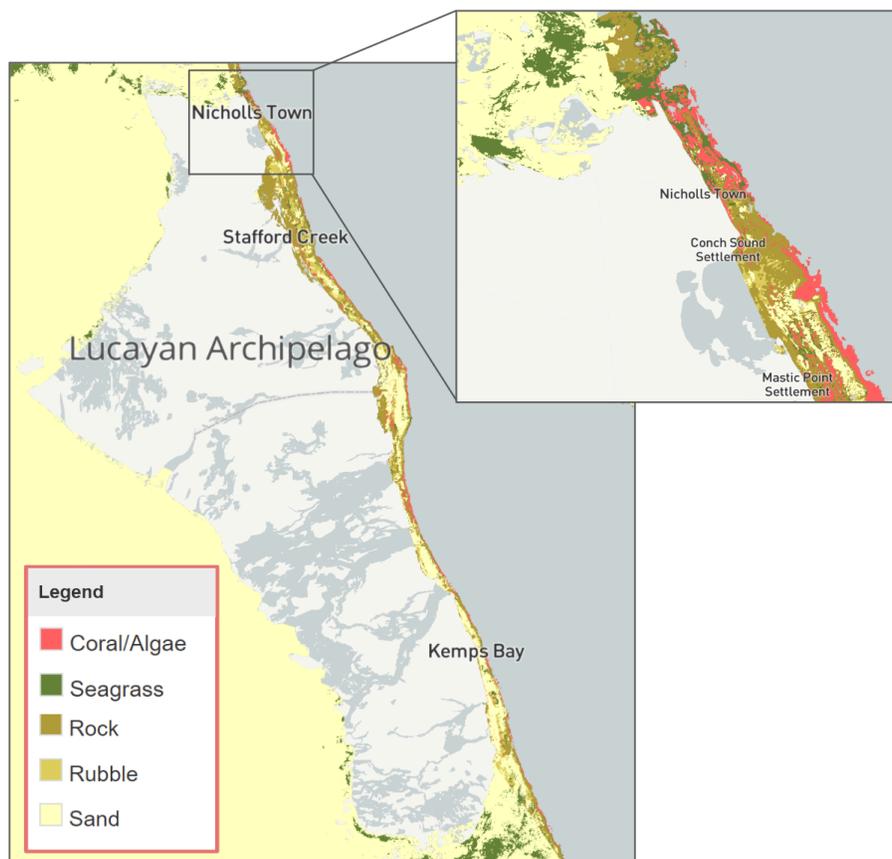
Figure 25. Map from Coral Health Atlas showing Andros Barrier Reef (Coral/Algae), other coastal marine environments (Seagrass) and substrates (Rock, Rubble, Sand). The expanded box shows the area that mining operations will most directly impact.

Blasting and Noise Pollution

In the ocean, visual navigation is unreliable, forcing animals to use sound for most aspects of daily life. Marine mammals use sound actively and passively in all biologically important behaviors (Tyack, 2000), such as socializing, traveling, hunting, breeding, and parenting (Gordon and Tyack, 2002; Dudzinski et al., 2009; Richardson et al., 2013; Erbe et al., 2018, and references therein). Similarly, fish use noise to express distress and maintain their populations (e.g., Myrberg, 1981; Mann and Lobel, 1997; Amorim, 2006; Van Oosterom et al., 2016).

Given their reliance on sound, loud noise and vibrations from mining operations and increased ship traffic will severely impact marine life. Even if mining noise operations adhere to World Bank standards for industrial

zoning (70 dB), as noise travels through seawater, it will become amplified, reaching a volume equivalent to a motorcycle engine (101 dB). In noisy areas, fish, marine mammals, and invertebrates (i.e., lobster) become stressed (e.g., Slabbekorn et al., 2010; Filicicotto et al., 2014; Armstrong-Smith, 2016; Staaterman et al., 2020), and over time, experience damage to auditory tissues and hearing loss (e.g., Popper and Hastings 2009a; Slabbekorn et al., 2010; Ladich, 2013 and references therein). With impaired hearing, fish and mammals will struggle to communicate and navigate their environment (e.g., Montgomery et al., 2006; Cotter, 2008; Ladich, 2019), making it difficult to detect and avoid predators, find food and potential mates (Richardson et al., 2013; Popper and Hawkins, 2016; Erbe et al., 2016; 2018). Locals on Grand Bahama reported fish kills associated with blasts from a limestone mining operation at Bahama Rock similar to the proposed operation on Andros. Bonefish and tarpon have been reported to float to the surface shortly after each quarry blast. With changes to the water table associated with quarrying activities, local fisheries have also been compromised up to 32 km from the mining operation at Bahama Rock (Stimpson 2022, Conservation). Cumulatively, these changes will detrimentally impact local biodiversity and the industries it supports.

Invasive Species

Beyond noise impacts, large vessels could affect biodiversity by introducing invasive species and diseases through their ballast water. Empty cargo ships fill their ballast tanks with seawater to enhance stability during transport, and release it before picking up cargo. In the process, ships unintentionally transport and release non-native species and pathogens from their port of origin. Ballast water is a primary way species invade new environments (e.g., Ruiz et al., 2000; Williams et al., 2013), and invasive species are a leading cause of global biodiversity change (e.g., McKinney and Lockwood, 1999; Sala et al., 2000). In the Caribbean region, ballast water has introduced green mussels (e.g., Buddo et al., 2003; Gobin et al., 2013) and stony coral tissue loss disease, which is wreaking havoc on Bahamian reefs (e.g., Dahlgren et al., 2021; Studivan et al., 2022). Notably, the disease was introduced by ships traveling from Florida, the most likely trade route for limestone aggregate.

Vessel Strikes

Frequent ship traffic could also drive an uptick in vessel strikes. Vessel strikes are defined as a forceful collision between any part of a vessel and a marine animal. Sharks, whales, and turtles are most susceptible to vessel strikes because of their long-range ocean movements, large body size, and need to bask and breathe at the surface (Pirotta et al., 2018). In the context of Andros Barrier Reef, strikes are particularly concerning for the five species of sea turtles, who are already under significant vessel threat during other parts of their migration. In South Florida, up to 60% of stranded loggerhead turtles show signs of propeller injuries (Conant et al., 2009), and from 2004-2008 in Georgia, United States, vessels and their propulsion systems were responsible for 23% of sea turtle fatalities (Work et al., 2010). All impacts to highly migratory species will be felt far beyond Bahamian borders.

Habitat Fragmentation and Degradation

To accommodate large transport vessels, which require deep water and large docks, developers must remove large volumes of sand, coral, and seagrass from the seafloor (Figure 26a). This process, called "dredging," is especially concerning for many reasons. Joulter Cays National Park and North Marine Park are some of the few

protected areas on the island where less than 5% of seagrass are at risk of degradation, compared to over 98% at high risk throughout the barrier reef area (Arkema et al., 2017).

Back on land, mining development would directly impact coastal wetlands by fragmenting habitat. Habitat fragmentation is "a process that turns an expansive habitat into numerous smaller habitats isolated from one another and unlike the original" (Fahrig, 2003). Bahamian studies comparing fragmented and unfragmented tidal creeks found that unfragmented creeks had "more reef-associated, economically important and ecologically critical plant, macroinvertebrate, and fish" compared to fragmented systems (Valentine-Rose et al., 2007a). Additionally, fragmented tidal creeks have fewer resource pools and a simpler food web structure than non-fragmented pools (Valentine-Rose and Layman, 2011; Valentine-Rose et al., 2011).

Sedimentation

Removing pine forests and seafloor to accommodate mining pits and harbors will increase sediment influx to coastal ecosystems, limiting light availability. Removing trees and plant material on land will make the landscape less capable of absorbing water. During increasingly frequent storm events (see Coastal Protection), water will move more quickly across the land, carrying large quantities of sediment out onto reefs and seagrass beds (e.g., Baumgartner et al., 1980; Fitzpatrick and Knox, 2000; Restrepo et al., 2015). Other Bahamian mining operations list these impacts as "moderately adverse" for adjacent ecosystems (Envirologic International Ltd., 2008). At sea, dredging and enhanced vessel traffic will raise water turbidity (murkiness), limiting light penetration, as seen elsewhere in Bahamian coastal mine development (Envirologic International Ltd., 2008).

Light limitation significantly reduces seagrass and coral photosynthesis, growth, and survival (e.g., Newell and Koch, 2004; Fabricius 2005 and references therein). Minimizing photosynthesis would reduce the harbor's seawater dissolved oxygen levels (photosynthesis produces oxygen), making it difficult for fish and invertebrates (i.e., Queen conch, Spiny lobster) to move and breathe (e.g., Brown and Robert 1968; Windham and Stickney, 1976 and references therein). Cumulative impacts will limit, if not eliminate coral reefs' and seagrass beds' capacity to serve as functional habitats.

Figure 26. (a) Proposed expanded harbor area (blue box), (b) satellite imagery and (c) habitat map demonstrating the area (dashed box on both) that would be impacted by harbor expansion.

Flood and Storm Resilience

Keeping up with Sea Level Rise

Over 150 million years, accumulated carbonate sediments rose above sea level to form the Bahamian islands (e.g., Meyerhoff and Hatten, 1974). These sediments are made up of calcium carbonate minerals, which marine plants and animals secrete. Sediments form a type of land termed "carbonate platform", which only exist in environments that support the growth of corals and other reef-building organisms (e.g., Wilson 1974; Read 1985).

Over thousands of years, wetland habitats accumulate soils, forming "peat" beds that can be 6 m deep or more (e.g., Ellison 1993; Ezcurra et al., 2016; Woodroffe et al., 2016 and references therein; Kida and Fujitake 2020 and references therein). Mangroves trap river and coastal sediments, binding it with their roots, leaves, and woody material to form soils (Spalding et al., 2014). Wetland soils are so void of oxygen that decomposition is slow, allowing the peats to grow vertically at rates of 10-18 mm per year or more (Spalding et al., 2014; Lenz et al., 2023). Their growth helps coastal areas keep pace with rising sea levels.

For The Bahamas to remain above sea level, the growth of reef-building organisms (i.e., corals) and peats must continue accumulating carbonate structures and sediments at rates that outpace sea level rise, erosion via storms, and human disturbance. Modeling studies for the Bahamas predict that sea level will rise by 32 cm (1.04 ft) by 2050 and 82 cm (2.68 ft) by 2100 (Strauss & Kulp, 2018; Figure 27). If sea level rises by 1 m, the Bahamas would lose 12% of its total land mass (IPCC, 2014). As seas rise, Bahamian islands rapidly lose material through storm erosion and human disturbance. Hurricanes have already severely eroded beach sand and dune faces, destroyed vegetation, and generated rock rubble (Curran et al., 2000).
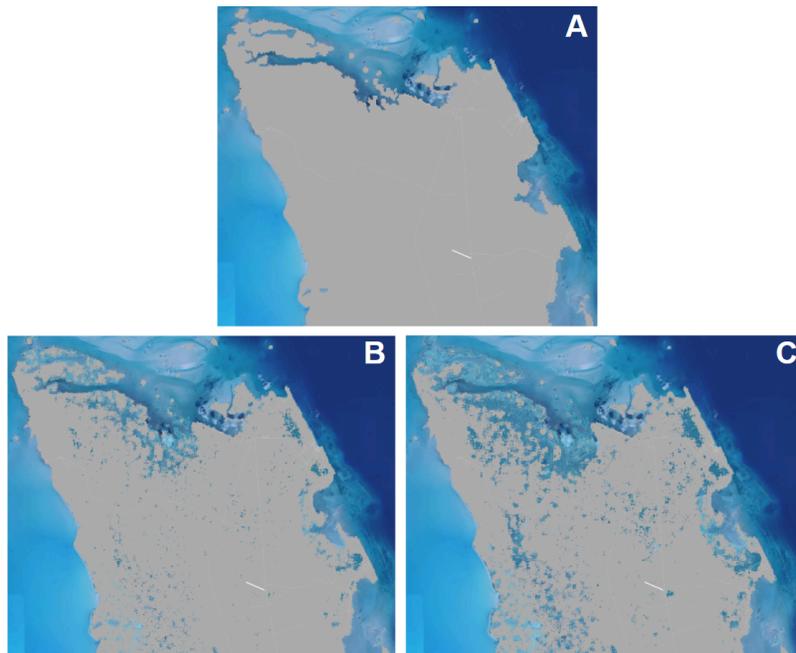

Figure 27. (a) Map of North Andros showing current sea level, (b) 0.33 m of sea level rise, and (c) 1 m of sea level rise. Images rendered using Climate Central Surging Seas: Risk Zone Map.

Coastal Protection

While contending with sea-level rise, Andros and other Bahamian islands are at significant risk of coastal flooding and devastation from hurricanes (National Hurricane Center, National Oceanic and Atmospheric Administration (NOAA), 2014). Between 2019 and 2023, 18 hurricanes landed in The Bahamas (World Data Info 2023), with Hurricanes Isaias, Sally, and Eta directly impacting North Andros. Hurricanes damage coastal communities with strong winds, rain, and storm surges—a temporary rise in seawater caused by winds pushing water onshore.

As climate change progresses in the North Atlantic, storms become more destructive and harmful to coastal communities (e.g., Knutson et al., 2007; Mann and Emanuel 2011; Colbert et al., 2013). Warm ocean and air temperatures, moist atmospheres, and rising sea levels create stronger, wetter, and slower-moving hurricanes (Trenberth et al., 2018; Gutmann et al., 2018). Storms intensify at unprecedented rates just before landfall, where they stay around longer, flooding communities with torrential rain and multi-story storm surges (Yates et al., 2014; Garner et al., 2017). In the aftermath, residents lose power, water, sanitation systems, and food security, commonly resulting in vector-borne disease and post-traumatic stress disorder, amongst other negative physical and mental health outcomes (Neria and Shultz., 2012; Schmeltz et al., 2013; Yates et al., 2014; Clay et al., 2018).

One of the best ways to protect Andros from hurricanes, flooding, and sea level rise is to preserve its coastal ecosystems. Coastal ecosystems reduce wave energy, absorb floodwaters, and prevent shoreline erosion (Silliman et al., 2019; Costanza et al., 2021; Castagno et al., 2022). Tidal flat wetlands reduce the height and energy of wind and swell waves passing through them, minimizing erosion and damage to structures, dikes, sea walls and other nearby infrastructure (Spalding et al., 2014; Reed et al., 2018). Likewise, the 3D structure of coral reefs dissipates wave energy by up to 97% (Ferrario et al., 2014). Dampening incoming wave energy also dampens outgoing wave energy, minimizing erosion by lessening the amount of material carried to sea.

While 70 km of Andros' east coast is highly vulnerable to storms and sea-level rise, coastal ecosystems reduce high risk and vulnerability for almost 71% of Andros' eastern coastline, protecting half of the island's population and income (Arkema et al., 2017). These habitats provide $3.9 billion per square kilometer in coastal protection, $120 million in erosion control, and an additional $6.8 million per km^2 in disturbance regulation (Hargreaves-Allen 2010, 2016).

Previously discussed mining impacts of habitat fragmentation, degradation, sediment runoff, and pollution all affect reef-building organisms' capacity to compete with sea level rise. Sediment runoff creates low light availability and unfavorable water chemistry in coastal waters, hindering the growth of reef-building organisms (e.g., Dodge et al., 1974; Miller and Cruise, 1995; Nugues and Roberts, 2003). Further, mechanical damage from dredging would significantly reduce the structural complexity of reefs. Degraded reefs would not be effective at mitigating coastal erosion (Reguero et al., 2018), attenuating waves (Harris et al., 2018), and other aspects of shoreline protection (Elliff and Silva, 2017).

Similarly, if fragmented, degraded, or lost, wetlands may lose their capacity to protect coastlines. Multiple sites of proposed mining development, including the smaller of the two proposed open pits (Figure 13), will leave small strips of mostly wetland between the ocean and the proposed infrastructure. These smaller, fragmented

areas will have little capacity to reduce wave and storm surge height and resulting flooding (McIvor et al., 2012; Spalding et al., 2014 and references therein; Montgomery et al., 2019). In an intensive development model of Andros, Arkema et al. (2017) found that Andros would lose significant coastal protections if mining were permitted. Further, if open pit structures expose accumulated peat and other unconsolidated coastal sediment, they will severely restrict, if not destroy the habitats' capacity to trap and accumulate sediment (Spalding et al., 2014 and references therein). These areas would shift from sites of sediment accumulation to sediment erosion.
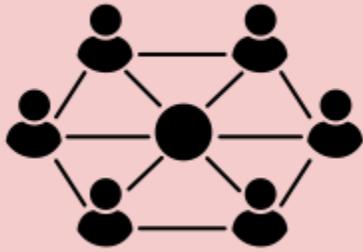
	Building Resilience: The Human Connection

Human Health and Well-being

Hazards to human health and well-being are present at every stage of the limestone mining process. Sources of potential human health issues include noise pollution, dust and noxious emissions, ground vibration, environmental contamination, water scarcity, and sexual violence. These hazards impact mine workers and nearby residents alike.

<u>Noise Exposure</u>

Noise pollution can negatively impact both auditory and non-auditory health. According to Sudhakar et al. (2022), "apart from dust, noise is the most common and recurring environmental stress in mining sites" (p. 751). Mining is among the sectors with the highest instances of noise exposure and related health issues (Themann and Masterson, 2019). Every day noise-related health hazards are outlined in Table 2 as a frame of reference for understanding mining-specific noise hazards, which are detailed in the following text. While mine workers will no doubt face the greatest intensity of mine noise, residences, schools, and businesses within a few kilometers of the mine site will be impacted by noise pollution as well. Several noise mapping models have shown noise upward of 30 dB from mine sites, processing plants, and haul roads several kilometers away (i.e., Baffoe and Duker, 2018 and Lokhande et al., 2017). Even these noise levels, comparable to a soft whisper, can have severe health impacts with extended exposure. While it is impossible to fully assess the intensity and extent of noise from the proposed mining operations without further study, places that may be negatively impacted include: North Andros High School, Lowe Sound Primary School, Clara Evans Primary School, Nicholls Town, and Conch Sound Settlement.

According to the Centers for Disease Control and Prevention (CDC), hearing damage can occur at or above 70 dB over long periods of time (Table 2) (2022). A 2023 study by Wang et al. found that among surface mine workers, excavation workers had a median noise exposure of 89.1 dB, mill operators of 88.7 dB, and crusher operators of 87.0 dB. At noise levels of 80-115 dB regularly recorded in active limestone quarries, workers are at risk of noise-induced hearing loss (NIHL) and deafness after prolonged exposure (Sudhakar et al., 2022). Despite increased safety regulations and standards, NIHL is a prevalent health issue in occupational settings (Basner et al., 2014; Mandal et al., 2022). If sound levels are intense and extensive enough, residents living near mining operations can suffer hearing damage and loss over prolonged periods. Children exposed to heightened noise levels for extended periods of time are at increased risk for accelerated inner ear aging and associated

hearing loss (Basner et al., 2014). When hearing loss occurs, auditory sensory cells in the inner ear die. These cells cannot regenerate, thus any loss of auditory cells and resulting impacts to hearing are permanent (Basner et al., 2014). In the early stages of hearing loss, a person loses the ability to detect high frequency noises (i.e., a child speaking) (Sudhakar et al., 2022). As the person gradually becomes deaf, perceiving sounds clearly and at wider frequency ranges becomes more difficult (Mandal et al., 2022). Normal speech becomes difficult to understand, which can have negative social implications. Cognitive performance can also decline with NIHL (Basner et al., 2014). Additionally, persons with occupational NIHL are at risk of "sleep disturbances, psychological stress, fatigue, and cardiovascular problems" (Ntlhakana et al., 2020, p. 1). A study by Deng et al. (2020) found that 84.2% of patients suffering from occupational NIHL eventually developed sleep disorders. If NIHL goes undiagnosed, it can lead to accidents and falls with an increased mortality rate (Basner et al., 2014).

Table 2. How different noise levels impact hearing (adapted from CDC, 2022).

Everyday Sounds and Noises	Average Sound Level (dB)	Typical Response After Repeated Exposure
Softest sound that can be heard	0	Little to no hearing damage
Normal breathing	10	Little to no hearing damage
Ticking watch	20	Little to no hearing damage
Soft whisper	30	Little to no hearing damage
Normal conversation	60	Little to no hearing damage
Shower	70	May feel annoyed
Busy traffic (from inside car)	80-85	May feel very annoyed; damage to hearing possible after 2 hours of exposure
Heavy truck	90-95	Damage to hearing possible after 50 minutes of exposure
Jackhammer	100	Hearing loss possible after 15 minutes
Shouting in ear	110	Hearing loss possible in less than 2 minutes
Sirens	120	Pain and ear injury
Firecrackers	140-150	Pain and ear injury

One symptom that often presents with NIHL is tinnitus (Basner et al., 2014; Passchier-Vermeer and Passchier, 2000). Tinnitus is more commonly known as "ringing in the ears". Tinnitus can be temporary with short periods of noise exposure, or permanent with prolonged occupational noise exposure (Passchier-Vermeer and Passchier, 2000, p. 125). According to Mandal et al. (2022), 50%-90% of patients experiencing chronic trauma from noise exposure also experience tinnitus. Like NIHL, tinnitus can also lead to other health problems like anxiety, depression, sleep disturbance, irritability, communication problems, and issues with attention span (Basner et al., 2014; Mandal et al., 2022).

Prolonged noise exposure can also cause non-auditory health issues. Annoyance is the most commonly reported issue among communities exposed to long-term environmental noise (Basner et al., 2014). According to Passchier-Vermeer and Passchier (2000), "noise annoyance is a feeling of resentment, displeasure, discomfort, dissatisfaction, or offense when noise interferes with someone's thoughts, feelings, or actual activities" (p. 126). Noise annoyance can also develop among industrial workers due to trouble communicating over loud noise at the work site (Mandal et al., 2022). Impacted workers and nearby residents often complain about "fatigue, irritability, and sleeplessness" associated with noise annoyance (Mandal et al., 2022, p. 143). Disrupted sleep patterns further contribute to feelings of annoyance and irritability (Passchier-Vermeer and Passchier, 2000). With continued noise exposure, annoyance can have severe effects on mental and physical health and wellbeing (Basner et al., 2014).

Several studies have linked noise exposure to sleep disruption in both humans and animals (Basner et al., 2014; Deng et al., 2020; Liu et al., 2021). A study of the Tarkwa Mining Community in Ghana showed positive correlation between noise exposure and noise-induced sleep problems (Baffoe et al., 2022). Noise-induced sleep disturbance is "thought to have the most deleterious non-auditory effect of environmental noise exposure because undisturbed sleep of a sufficient length is needed for daytime alertness and performance, quality of life, and health" (Basner et al., 2014, p. 1329). Sleep disturbance can occur at noise levels as low as 33 dB (the volume of a whisper) (World Health Organization, 2009 cited by Basner et al., 2014). Liu et al. (2021) also found heightened stress responses related to sleep disruption at noise levels beneath human perception and consciousness. Both daytime and nighttime exposure can have negative impacts on sleep (Liu et al., 2021). The most at-risk populations for noise-induced sleep disturbance are children, workers, and communities near the noise source (Basner et al., 2014). Short-term effects of sleep disturbance from noise exposure include daytime sleepiness, impaired cognitive performance, mood problems, nighttime awakening, habitual snoring, shorter sleep duration, and trouble falling asleep (Basner et al., 2014; Liu et al., 2021). Repeated noise interference with sleep can eventually lead to long-term intense fatigue and problems with cardiovascular and neurological functioning (Li et al., 2022).

Beyond annoyance, noise exposure can have adverse impacts on human endocrine functions resulting in heightened stress levels. A 2020 study by Lu et al. found that occupational noise exposure among factory workers increased risk of job stress by 1.39 times. According to Michaud et al. (2022), "exposure to noise can act as a stressor as evidenced through increased heart rate, blood pressure, epinephrine (adrenaline), and cortisol" (p. 866). Cortisol is a naturally occurring hormone produced in the adrenal glands and is responsible for regulating stress responses in the body, among other important functions. Several studies have shown that cortisol levels increase as a result of noise exposure, indicating increased stress levels in the presence of noise (Michaud et al., 2022). For example, children regularly exposed to traffic noise presented with heightened cortisol levels and chronic stress (Stansfeld and Clark, 2015). Sleep disturbance and NIHL resulting from noise

exposure can further exacerbate stress. Prolonged stress due to noise exposure is also believed to contribute to adverse stress-related health problems, like cardiovascular disease (Basner et al., 2014; Michaud et al., 2022).

While more research is needed to understand the relationship between noise exposure and cardiovascular issues, several studies have shown a positive correlation exists between the two (Baffoe et al., 2022; Basner et al., 2014; van Kamp et al., 2020; Li et al., 2019; Münzel et al., 2018a; Münzel et al., 2018b) (Figure 28). Cardiovascular issues associated with environmental and occupational noise exposure include hypertension, stroke, myocardial infarction mortality (death via heart attack), heart disease, and diabetes (Kerns et al., 2018; Li et al., 2019; Li et al., 2022; Münzel et al., 2018b). A 2022 study of the Tarkwa Mining Community in Ghana by Baffoe et al., found there was a positive correlation between mining noise pollution levels and cardiovascular diseases. Workers are at increased risk of developing cardiovascular issues due to prolonged occupational noise exposure (Li et al., 2022). A 1968 study by Jansen found increased cases of heart problems among industrial workers in noisy industries, as opposed to those working in less noisy environments (cited by Münzel et al., 2018b). Another study found that 14% of hypertension and 9% of elevated cholesterol cases among U.S. industry workers could be traced to occupational noise exposure (Kerns et al., 2018). Additionally, worker risk of developing hypertension and elevated cholesterol increases with increased noise exposure time (Basner et al., 2014; Kerns et al., 2018; Li et al., 2019). Dehghan and Gharib (2016) also found that noise levels above 85 dB in hot and humid climates exacerbated adverse effects on workers' heart rates. This is particularly concerning as mine noise levels regularly exceed 85 dB and the climate of Andros is hot and humid year-round, which will likely get worse with climate change. Residents living near the quarries and haul roads are also at risk of developing cardiovascular diseases from exposure to noise from mining operations. Several studies have found a positive correlation between road traffic noise and cardiovascular diseases - like hypertension, heart attack, arrhythmia, heart disease, and heart failure - in residents living near roads (Münzel et al., 2018a; Münzel et al., 2018b; Münzel et al., 2021). In Europe alone, 900,000 cases of hypertension, 48,000 cases of ischemic heart disease, and 12,000 premature deaths due to long-term environmental noise exposure are recorded each year (European Environment Agency, 2018 cited by Münzel et al., 2018b; European Environment Agency, 2020 cited by Münzel et al., 2021). Cardiovascular risk from noise exposure increases with nighttime exposure above 55 dB and presence of air pollution (Münzel et al., 2018b). This is especially concerning as modern mines typically operate 24/7, consistently produce noise greater than 55 dB, and produce noxious gas emissions and dust pollution.
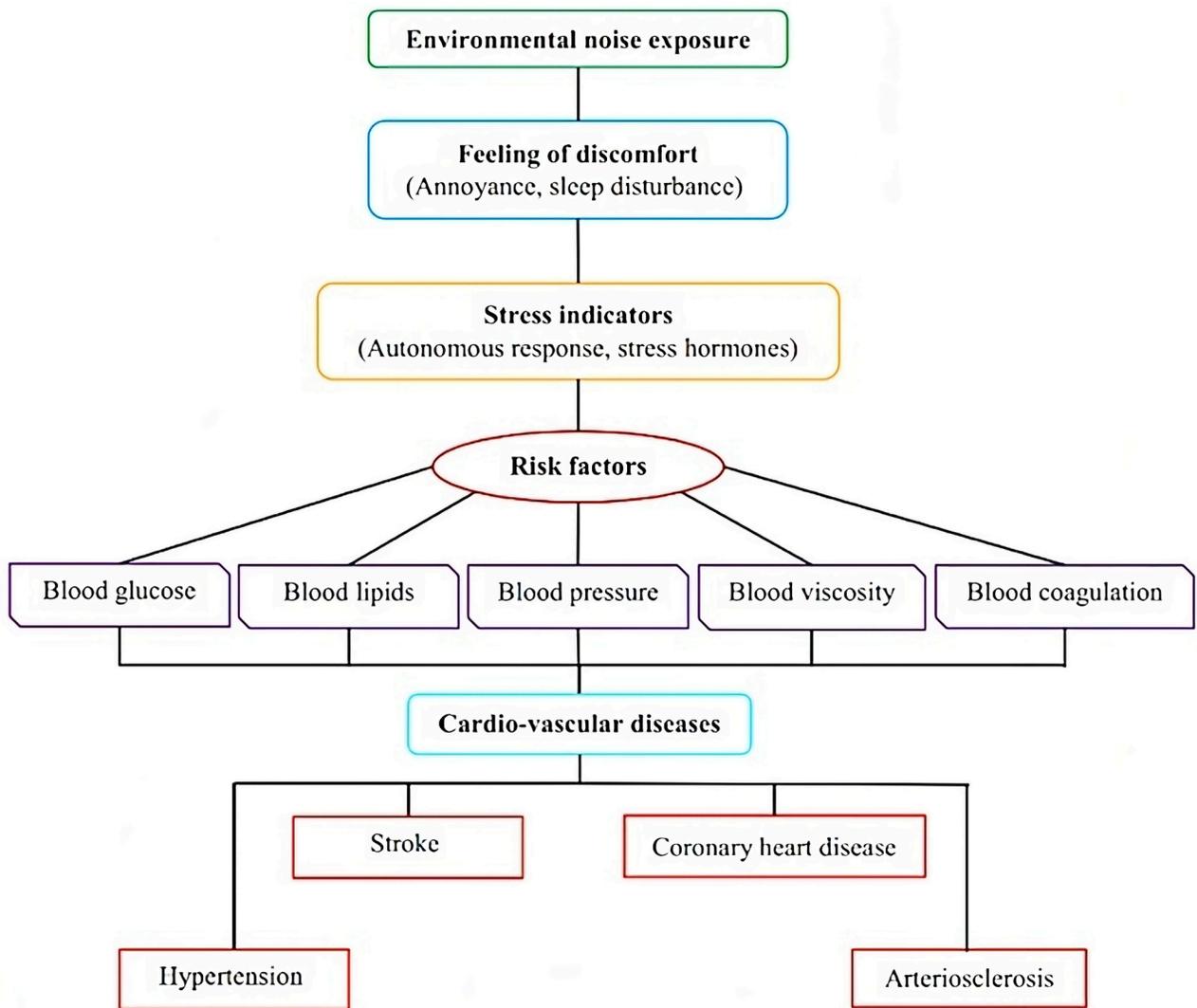
Figure 28. Progression of the development of cardiovascular diseases from environmental noise exposure (from Zaman et al., 2022).

Studies have yielded mixed results on the relationship between noise exposure and mental health issues, but many point to a positive correlation between the two. According to a study by Beutel et al. (2016), mental health problems like anxiety and depression are linked to elevated environmental noise levels (cited by Münzel et al., 2018a). Jafari et al. (2022) found that patients suffering from chronic noise exposure also experienced anxiety, depression, decreased cognitive function, and lower quality of life. Dementia and Alzheimer's risk has also been reported to increase with increased noise exposure during the night (Zaman et al., 2022). In a study by Lu et al. (2020), noise increased psychological health problems for factory workers and miners by 123%. Industrial workers suffering from occupational NIHL are at increased risk of developing psychiatric disorders. Deng et al. (2020) reported that 53.8% of industrial workers with occupational NIHL experienced depressive symptoms, with 27.4% suffering from mild depression, 19.8% from moderate depression, and 6.6% from severe depression. Workers with occupational noise-induced tinnitus also suffered from higher levels of anxiety and depression (Deng et al., 2020; Jafari et al., 2022). Studies on traffic and residential noise can also give insight into potential

impacts of mining noise on mental health of nearby residents. Research has shown that residential and traffic noise contributes to anxiety and depression (Hegewald et al., 2020; Lan et al., 2020; Zaman et al., 2022). One study found a 12% increase in anxiety and a 4% increase in depression per 10 dB increase in traffic noise above 55 dB (Dzhambov and Lercher, 2019); another found a 9% increase in anxiety per 10 dB increase in traffic noise (Lan et al., 2020). Stansfeld et al. (2021) found that road traffic noise was specifically associated with severe and suicidal depressive symptoms. Traffic noise also potentially increases the risk of Alzheimer's in adults as a result of sleep disturbance and stress (Zaman et al., 2022). Noise annoyance (described above) may be another mediator between noise exposure and mental health disorders, depressive symptoms, and antidepressant use (Eze et al., 2020 and Dzhambov et al., 2017 cited by Stansfeld et al., 2021; Beutel et al., 2016, Jensen et al, 2018, and Okokon et al., 2018 cited by Zaman et al., 2022).

Of the 11 primary and secondary schools on Andros - 3 of which are temporarily closed as of August 2023 - 3 are within a few kilometers of the proposed mine site and potential haul road locations (Figure 29). This is concerning as children are especially vulnerable to health (detailed above) and cognitive issues induced by environmental noise (Gupta et al., 2018; King, 2022; Makles and Schneider, 2017; Schubert et al., 2019). In terms of cognition, noise exposure primarily affects central processing and language comprehension (Stansfeld and Clark, 2015). Documented effects include impaired memory, problem solving abilities, reading and writing skills (Stansfeld and Clark, 2015; Klatte et al., 2013), attention span (Murphy and King, 2022), speech perception, and listening comprehension (Klatte et al., 2013) (Table 3). The highly cited RANCH study of nearly 3000 children between the ages of 9 and 10 years showed a linear relation between aircraft exposure during school hours and decreased reading comprehension and recognition memory (Stansfeld et al., 2005 and Clark et al., 2006). For each 5 dB increase in noise exposure, children suffered a 1-2 month reading age delay (Basner et al., 2014). According to Makles and Schneider (2017), noise pollution can still be detrimental to cognitive development in children at levels produced by road traffic, which is particularly concerning with respect to the proposed mine in Andros due to the added presence of haul road traffic (80-95 dB). These noise levels greatly exceed the World Health Organization's recommendation of a maximum noise level of 35 dB during teaching sessions (Berglund et al., 1999 cited by Basner et al., 2014). A study of three primary schools in Malaysia reported the highest noise levels at the school located near an industrial area, with noise-exposed children suffering from shorter attention spans and behavioral issues (Ismail et al., 2015). The primary contributors to noise level in a similar study of a school in an industrial area of Malaysia were heavy trucks (Abdullah et al., 2021), like those that would be required to haul limestone aggregate within and outside of the proposed mine site on Andros. A study by Schubert et al. (2019) found evidence linking road traffic noise to increased hyperactivity and inattention in children. Poorer reading comprehension and memory (Haines et al., 2001 cited by Stansfeld and Clark, 2015), ADHD (Forns et al., 2016), and lower scores on national standardized tests (Hygge et al., 2002, Bronzaft, 1981, and Lercher et al., 2003 cited by Basner et al., 2014) are also adverse effects reported in children exposed to traffic noise during school. Three studies for children (9-10 years old) and adolescents (15-17) found an 11% increase of hyperactivity and inattention per 10 dB of road traffic noise during school hours (Schubert et al., 2019). A 2016 study on preschool children exposed to continuous road traffic noise found that for each 10 dB increase in noise, children fell behind by 3 months in kindergarten (Makles and Schneider, 2017). Traffic noise during sleeping hours also led to decreased sleep, which negatively impacts physical growth and cognitive development, and may explain increasing behavioral and emotional issues. Gupta et al. (2018) reported decreased well-being and cognitive performance among children exposed to nighttime traffic noise. Thus, potential noise impacts to children's learning from the proposed mining operation in Andros could compromise the United Nations Sustainable Development Goal (SDG) of a quality education.

Table 3. Summary of cognitive impacts in children from noise exposure (adapted from Pakulski et al., 2016).

Evidence of Academic Concerns Linked with Unfavorable Noise-Scapes
Compromised oral language comprehension and reading acquisition (Haines et al., 2001a and 2001b; Schafer et al., 2013) and difficulty categorizing speech sounds (Klatte et al., 2007)
Poorer scores on standardized tests of literacy, mathematics, and science (Shield and Dockrell, 2008)
Decreased intelligibility of speech (Crandell and Smaldino, 2000; Yang and Bradley, 2009), and poorer performance on phonological discrimination tasks (Klatte et al., 2005)
Negative effects on cognition including short- and long-term memory (Klatte et al., 2010), intentional, incidental, and recognition memory (Lercher et al., 2003), and disrupted memory for nonwords (Klatte et al., 2007)
Increased levels of fatigue, stress, and annoyance (Bess et al., 2014; Klatte and Hellbrück, 2010; Klatte et al., 2010; Mealings et al., 2015)
More difficulty communicating with teachers and peers (Klatte et al., 2010; Mealings et al., 2015)
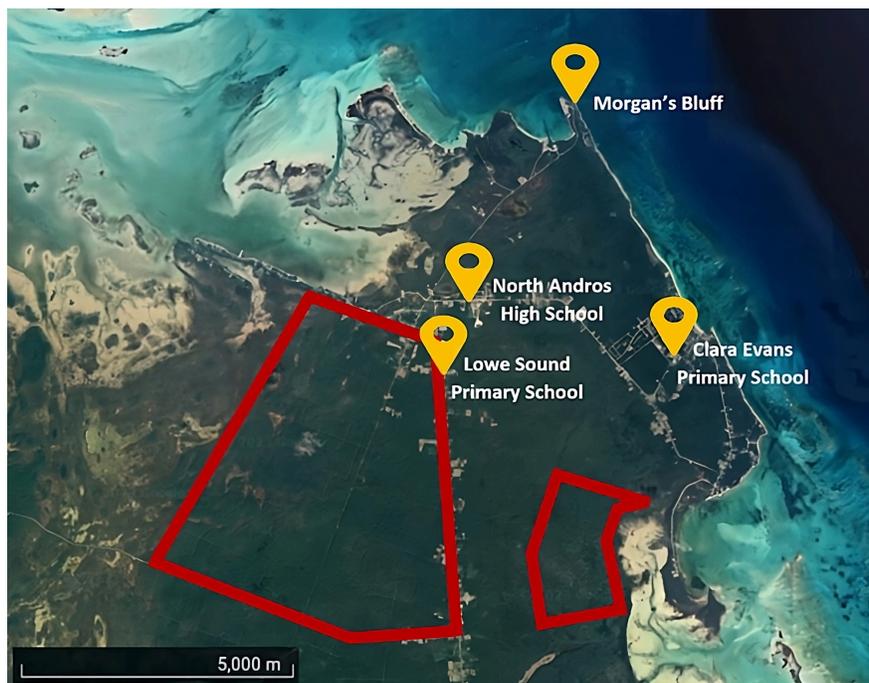
Figure 29. Locations of primary and secondary schools (yellow) in North Andros relative to proposed quarries (approximate - red) as of August 2023.

Studies have not produced consistent evidence of associations between birth outcomes and noise exposure, however there is preliminary evidence that noise exposure may impact pregnancy and birth (Stansfeld and Clark, 2015). According to Gupta et al. (2018), "pregnant women, fetus, newborns, and infants" are among the

groups most susceptible to adverse health effects due to noise exposure (p. 300). Some studies indicate that noise exposure during pregnancy can lead to low birthweight and possibly premature birth (Dzhambov and Lercher, 2019; Smith et al., 2020; Stansfeld and Clark, 2015). Studies have also shown hearing impairment and non-auditory adverse health effects in babies born to mothers exposed to occupational noise during pregnancy (Gupta et al., 2018; Selander et al., 2016). Increased environmental noise exposure during pregnancy may also lead to prenatal anxiety and depression (Jigeer et al., 2022). If exposure to noise continues beyond the pregnancy, mental health issues can develop and worsen for the mother (He et al., 2019). According to Jigeer et al. (2022), women of lower socio-economic status are at increased risk of developing mental health issues as a result of noise exposure before, during, and after pregnancy. Low birthweight, premature birth, and pregnancy-related mental health issues are all potential health hazards for mothers living in close proximity to the mine site and haul roads.

<u>Dust and Gaseous Emissions</u>

Relatively little work has been done to study air quality in the context of limestone mining (Lamare and Singh, 2017; Amitshreeya and Panda, 2012 cited by Ambastha and Haritash, 2021). It is especially important to note that most of these studies have occurred in Africa and Asia, with no studies found pertaining to Caribbean contexts. Due to the lack of Bahamas-specific case studies in this context, information relating to air quality and health impacts from limestone mining operations is documented more broadly in this section.
Despite this lack of research, studies agree there is a direct link between limestone mining dust and emissions, and human health (Etim et al., 2021; Mishra et al., 2004; Raysoni et al., 2022). Aggregate mining can result in both localized and distant air quality issues, as airborne pollutants can be carried by wind currents great distances from the mine site (Ambastha and Haritash, 2021; Awwad et al., 2015; Etim et al., 2021; Raysoni et al., 2022; Ukaogo et al., 2020). A study by Ambastha and Haritash (2021) found that calcite dust had the potential to spread up to 4 km vertically and 40 km laterally from a mine site in under 4 hours. Air pollution in general can trigger existing respiratory conditions like asthma, impair lung function, and lead to the development of chronic conditions like lung cancer, chronic obstructive pulmonary disease (COPD), and emphysema (Dhatrak et al., 2014; Legator et al., 1998 cited by Jayadipraja et al., 2016). Vulnerable groups like pregnant women, the elderly, children, people experiencing poverty, mine workers, and those with preexisting adverse health conditions are at higher risk (Bertoldi et al., 2012 cited by Jayadipraja et al., 2016; Dhatrak et al., 2014). Limestone mining produces two types of air pollution that can have negative impacts to human health and the environment: particulate matter and gaseous emissions.

Suspended particulate matter (SPM) is the main air quality concern as it relates to limestone mining (Ghose and Majee, 2000 cited by Lamare and Singh, 2017; Suryaman and Rahman, 2011; Ukaogo et al., 2020). SPM is produced at several points in the limestone mining process including drilling, blasting, crushing, sorting, hauling and transport by both truck and conveyors (Ambastha and Haritash, 2021; Chaulya et al., 2001; Lamare and Singh, 2017; Mankar et al., 2019; Mishra et al., 2004; NIOSH, 2010 cited by Akande and Ifelola, 2011; Raysoni et al., 2022). The majority of particulate matter (PM) from limestone mining consists of dust, smoke, and dirt particles (Raysoni et al., 2022). PM refers to any microscopic solid or liquid that can be inhaled (<10 microns in size), and thus have potential to cause serious health problems (Awwad et al., 2015; US EPA, 2023). Quarrying processes can produce PM that ranges in size from coarse to fine (Bluvshtein et al., 2011 cited by Peng et al., 2016). PM small enough enter the bloodstream (<10 microns, PM_{10}) can cause short- and long-term adverse health effects (US EPA, 2023). Particulate matter 2.5 microns ($PM_{2.5}$) or smaller poses the greatest risk to

human health (Schlesinger, 2007 cited by Etim et al., 2021; US EPA, 2023). With respect to limestone mining operations, PM can be found in greatest concentrations along haul roads and crushing units (Ambastha and Haritash, 2021). In 2017, $PM_{2.5}$ inhalation resulted in 2.9 million premature deaths and 9% of total deaths globally (Croituru et al., 2020 cited by Etim et al., 2021). 60% of the premature deaths from $PM_{2.5}$ in Nigeria were children under 5 (Croituru et al., 2020 cited by Etim et al., 2021). Quarrying and stone crushing is a major source of $PM_{2.5}$ and PM_{10} globally, accounting for up to 50% of dust accumulation in mining regions (Jain and Khare, 2010 cited by Ambastha and Haritash, 2021).

Respiratory issues are among the predominant health issues found in workers exposed to dust from mining, crushing, and transport of stone (Ambastha and Haritash, 2021; Awwad et al., 2015; Nwibo et al., 2012). Respiratory issues like chest pain, cough, shortness of breath, trouble breathing, sputum mixed with blood, and wheezing were reported among quarry and stone crushing workers in Nigeria, Iran, and Brazil (Lemele et al., 1994; Mashaallah et al., 2006 cited by Nwibo et al., 2012). Communities downwind from mining operations are also at increased risk of developing respiratory and other health issues as a result of dust exposure (Ambastha and Haritash, 2021). According to Suryaman and Rahman (2011), of community members living in proximity to mining operations, children are the most at risk of developing health problems from air pollution. In the same study, they found that only 9% of residents within 3 km of the limestone mine were safe from PM health risks. Rahman et al. (2008) found that the 'safe area' from human health risk due to PM for residents was greater than 4.5 km from the mine site (cited by Suryaman and Rahman, 2011). It is important to note these results are context-dependent on factors like topography and meteorological conditions (Peng et al., 2016), but is still concerning for Andros residents as several residences and primary schools exist well within 4.5 km of the proposed quarry sites. A 2004 study by Mishra et al. found that despite PM levels within prescribed limits, limestone quarry workers and nearby residents reported increased cases of tuberculosis. Another study by Sukabumi (2005 cited by Suryaman and Rahman, 2011) found that residents living near a limestone mine reported double the amount of respiratory complaints than those living outside of mining areas. Raysoni et al. (2022) also found adverse health effects associated with PM exposure among residents living near a limestone mining area.

Long-term exposure to PM from limestone mining can result in more serious conditions like chronic obstructive pulmonary disease (COPD) (Suryaman and Rahman, 2011), an inflammation of the lungs that impairs their ability to oxygenate. COPD was the third leading cause of death in 2019 (WHO, 2020). Additional health effects caused by long-term $PM_{2.5}$ exposure include cardiac and lung disease, heart attack, irregular heartbeat, asthma, and reduced lung capacity (Jain and Khare, 2008 cited by Ambastha and Haritash, 2021). A study by Doig (1955) also found several cases of pneumoconiosis among limestone mining workers working with crushers and grinders over a period of several decades (cited by Mankar et al., 2019).

Silica dust exposure is another concern in limestone mining areas, and presents an additional set of health risks for those exposed, especially mine workers (Healy et al., 2014 cited by Mankar et al., 2019). Crystalline silica dust is highly associated with $PM_{2.5}$ (Csavina et al., 2012; Gholampour et al., 2016; and Kurilić et al., 2020 cited by Raysoni et al., 2022). Limestone can contain a range of silica quantities, with some containing as much as 40% crystalline silica (Mankar et al., 2019). Additional studies would need to be conducted on the limestone in the proposed mining area in North Andros to determine its crystalline silica content; however, it is unlikely that silica will be of concern due to the compositional purity of limestone in The Bahamas.

Health risks associated with crystalline silica dust inhalation vary based on exposure times. In the short term, individuals exposed to crystalline silica dust can suffer from suppressed immune function (Mankar et al., 2019)

and tuberculosis (Hnizdo and Vallyathan, 2003 cited by Mankar et al., 2019). Long-term exposure to silica dust, even at low levels, can also eventually cause cardiovascular disease, chronic bronchitis, lung cancer, airflow obstruction, rheumatoid arthritis, scleroderma, Sjogern's syndrome, lupus, renal disease (Mankar et al., 2019), and silicosis (Mankar et al., 2019 and NIOSH, 2010 cited by Akande and Ifelola, 2011; Raysoni et al., 2022). Silicosis is perhaps the most documented health impact associated with crystalline silica exposure, and occurs when inhaled crystalline silica dust scars lung tissue, which can be potentially fatal (Cauda et al., 2013 cited by Mankar et al., 2019; NIOSH, 2010 cited by Akande and Ifelola, 2011). Even when airborne silica is below the prescribed limit, those exposed can develop health risks like pneumoconiosis (Mankar et al., 2019). Chen et al. (2012) also reported increased mortality from cardiovascular disease in mine workers exposed to low concentrations of silica dust (cited by Mankar et al., 2019).

Gaseous emissions associated with limestone mining are produced by heavy machinery like bulldozers, draglines, drilling machines, dumpers, and transportation vehicles, like trucks and conveyors (Belardi et al., 2013 and Petravratzi et al., 2005 cited by Raysoni et al., 2022; Lamare and Singh, 2017). Gaseous pollutants produced by this machinery include carbon monoxide (CO), sulphur dioxide (SO_2), and nitrogen oxides (NO_x) (Jayadipraja et al., 2016; Lamare and Singh, 2016 cited by Ganapathi and Phukan, 2020; Suryaman and Rahman, 2011). Similarly to SPM, gaseous emissions can travel far beyond the mine site, thus polluting the air in nearby communities (Jayadipraja et al., 2016). When these gaseous pollutants are inhaled, the respiratory system is the first to experience negative health impacts. Over time, these pollutants can accumulate in the lungs and cause more serious long-term effects (Jayadipraja et al., 2016). NO_x exposure can lead to visual impairment, asthma, and lung tissue damage (Adeyanju et al., 2019 and Wufem et al., 2021 cited by Etim et al., 2021). NO_x emissions into the atmosphere can also exacerbate climate impacts (Adeyanju et al., 2019 and Wufem et al., 2021 cited by Etim et al., 2021). SO_2 exposure can also lead to respiratory complications. SO_2 in the atmosphere can also oxidize, forming SO_3, which can lead to surface water and soil acidification (Zhang et al., 2019 cited by Etim et al., 2021). Even when these gaseous emissions are below prescribed limits, there is evidence that cardiovascular health issues can arise (Münzel et al., 2018b).

Vibration

There are two kinds of concerning vibrations with respect to limestone mining operations: ground vibrations and airblast. Airblast originates from changes in air pressure during blasting and affects building sides and roofs (Kisi et al., 2021). Ground vibrations in limestone aggregate mining can originate from drilling and blasting, as well as haul trucks, crushers, and sorting screens. Ground vibrations affect structure foundations (Kisi et al., 2021). Of the sources of ground vibrations in mining operations, blasting is by far the most studied. These vibrations can directly impact both structures and humans.

Impacts of vibration on human health and safety warrants study in this context as human beings have high sensitivity to vibration, and can perceive vibrations below thresholds that are capable of causing structural damage (Ak et al., 2009). A study by Afeni and Osasan (2009) found that despite a Nigerian limestone mine taking measures to mitigate vibration, the vibrations produced were still detected by workers and residents near the site. Additionally, ground vibrations and airblast can cause shaking and damage to structures (Kisi et al., 2021). The majority of structural damage occurs when vibrations are within the natural frequency of that structure, resulting in resonance and thus the greatest potential for damage (Kisi et al., 2021). Most structures have low natural frequencies, similar to those of the vibrations produced by limestone blasting. A study by Farhad et al. (2014) found that 94% of ground vibration frequencies recorded during limestone blasting fell

between 1 and 14 Hz, with airblast frequencies all less than 15 Hz. These low frequencies considerably increased the possibility of structural damage due to being within structures' natural frequencies (Farhad et al., 2014). Ak et al. (2009) recorded similar results, with 98% of recorded frequencies below 40 Hz, and thus having high potential to cause structural damage. Common recorded damages include cracks to drywall and plaster walls and ceilings (Kisi et al., 2021). Older and weaker structures have lower vibration thresholds at which damage can occur (Hosseini and Baghikhani, 2013). Homes in North Andros may be at additional risk due to existing or potential future structural damage from tropical storm and hurricane events.

While several studies point to the potential for damage to structures from limestone mine blasting, several studies have found little risk of damage from such operations. A 2013 study by Hosseini and Baghikhani reported no risk of damage to structures within 1 km of blasting at the mine site. Another study in the US by Aimone-Martin and Ronsenhaim (2006) found that while vibrations were perceptible to humans in two structures within 4 km of limestone quarry blasting, no threshold cracking could be attributed to the blasting. In fact, crack displacement from activity in the home - like closing a door or dropping an object - recorded during the study period was 6 times greater than from blasting and 2 times greater from weather conditions, like humidity (Aimone-Martin and Ronsenhaim, 2006).

It is difficult to say if or how vibrations from the proposed limestone mining operation in North Andros would impact residential structures in the area. This is because the travel of vibrations depends on "(1) the amount of energy released at the source, (2) the distance from source to site, and (3) site characteristics" (Kisi et al., 2021, p. 2). Residents near the limestone mining operation at Bahama Rock have reported cracking walls, ceilings, and foundations, as well as "being blown off their couches" during blasting (Stimpson, 2022). Recommended further assessment would include developing vibration models and maps of the proposed mining activities in North Andros.

Researchers generally agree that mine-induced vibrations have detrimental health impacts on mine workers. Mine workers are especially at risk from both blasting vibration and equipment-induced vibration. Machine operators can experience both whole-body vibration (WBV, affects the entire body) and segmental vibration (affects one part of the body) (Mandal and Srivastava, 2006). Personnel who operate vibrating hand tools have increased likelihood of developing hand-arm vibration syndrome (HAVS) from segmental vibration affecting the hands and arms. Symptoms include tingling and numbness in fingers, and in extreme cases reduced blood supply to the fingers which can result in gangrene and if untreated, a need for amputation (Mandal and Srivastava, 2006). Sources of WBV in mining industries include seat-transmitted vibrations and ground vibrations while standing on crushers, vibrating screens, and loaders (Mandal and Srivastava, 2006). WBV can lead to a plethora of potentially serious health issues including back pain, sciatica, and spinal degenerative disorders (Bovenzi, 1999 cited by Mandal and Srivastava, 2006; Das et al., 2021). Digestive diseases can also arise due to stomach resonance (Griffin, 1998 and Seidel, n.d. cited by Mandal and Srivastava, 2006). Additionally, WBV at frequencies below 20 Hz can lead to issues like hyperventilation and increased heart rate (Griffin, 1998 and Seidel, n.d. cited by Mandal and Srivastava, 2006). Women workers have increased risk of suffering from varicose veins, spontaneous abortion, menstrual disorders, and hyperemesis gravidarum - severe nausea and vomiting - during pregnancy (Abrams, 1990 and Wasserman et al., 1997 cited by Mandal and Srivastava, 2006). Organs are at risk of more extreme adverse effects if ground vibration matches their natural resonance frequencies (Mandal and Srivastava, 2006).

<u>Sinkhole Collapse</u>

As discussed in prior sections, sinkhole formation can be exacerbated by changes to groundwater flow from limestone quarrying operations. Vibrations produced by blasting can also trigger sinkhole collapse. Ground deformation and sinkhole collapse can cause damage to human-built structures, from buildings to roads (Gutiérrez, 2016). Unexpected and sudden sinkhole collapse can harm humans as well, causing injury and even death. Wanfang (1997) adds that sinkhole collapse worsens the environment, triggers an alteration of geologic conditions, dries up wells and surface water sources, increases inflow of water from karst aquifers, leads to land subsidence, destroys man-made structures, threatens mine safety, and can cause injury and death of humans and animals. Most such sinkholes are cover-collapse sinkholes, which are difficult to detect and often collapse without warning (Weary, 2015) (Figure 30). According to Weary (2015), the US alone spends well over $300 million per year due to sinkhole damages. A list of major damaging sinkhole events in karst environments associated with resource extractive activities can be found in Table 4.

Figure 30. Cover collapse sinkhole triggered by groundwater level decline related to pumping in the Hotamis Plain, central Anatolia, Turkey. It was 25 m in diameter and 36 m deep at the time of formation in 2009. Two geomorphologists on the far edge of the sinkhole for scale (from Gutiérrez, 2016).

Table 4. List of major damaging sinkhole events in karst environments associated with resource extractive activities (adapted from Gutiérrez, 2016).

Year	Location	Subsidence Phenomenon	Damage	Relevant Factors
1962	West Driefontein Mine, Far West Rand, South Africa	Sudden bedrock collapse sinkhole, 55 m across	Engulfed a three-story crusher plant with the **loss of 29 lives**	Induced by **dewatering** for gold mining
1963	Liangwu Village, Guixian, Guangxi, China	157 collapse sinkholes within an area 1800 m long and 250 m across	**Village abandoned**	Induced by **explosions** conducted for groundwater exploration
1964	Blyvoorruitzicht, Far West Rand, South Africa	Bedrock collapse sinkhole	Four **houses damaged**, with **loss of five lives**	Induced by **dewatering** for gold mining
1974	Hutchinson, Reno County, Kansas	Cover and bedrock collapse sinkhole 90 m in diameter and 15 m deep (Cargill Sink)	Missouri-Pacific **Railways suspended** above crater	Collapse of a cavern spanning 400 m and created by **solution mining** since 1908 at about 130 m below surface
1981	Winter Park, Florida	Cover-suffosion collapse sinkhole 106 m across and 30 m deep	**Destruction of streets, utilities, one house, and several businesses**	Accelerated by decline of piezometric level by **pumping**
1998	Oviedo, Spain	Catastrophic collapse sinkholes; **Demolition** of one block with multi-story buildings	**€18 million**	**Dewatering** for excavation
2012	Assumption Parish, Louisiana	Rapidly expanding sinkholes more than 350 m in diameter accompanied by **methane gas escape**	Around 350 residents affected by **long-term evacuation**. Lawsuit involving around **$50 million**	Collapse of a cavern more than 1,000 m deep at the edge of a salt diapir created by **solution mining**

Sexual and Gender Based Violence

Sexual and Gender Based Violence refers to "any act that is perpetrated against a person's will and is based on gender norms and unequal power relationships" (UNHCR, n.d. cited by Atim et al., 2020, p. 9). The impacts of large scale mining (LSM) are disproportionately experienced based on gender, with women experiencing harms that are different from and often more violent than harms experienced by men (Simons and Handl, 2021). While not all resource extractive operations result in increased instances of SGBV, documentation exists that these issues are associated with large scale extractive activities globally. The potential for SGBV associated with the proposed operation in Andros depends on its own unique historical, geographical, and socioeconomic context. Recognizing further study is needed to comment on specific SGBV impacts associated with limestone mining in North Andros, below is a brief review of documented SGBV impacts associated with mining and resource extraction globally.

SGBV is a widespread issue in resource extractive industries globally, with many different manifestations (Cane et al., 2014; Atim et al., 2020; Simons, 2017). Forms of SGBV that women may experience as a result of resource extractive industries in or near their communities include poverty, physical and emotional abuse, sexual violence, domestic violence, workplace violence, and mental health problems (Hettinga and Dean, 2023). Such experiences are varied between women and depend on factors like country, age, race, and socioeconomic status (Simons and Handl, 2021). Women and girls of lower socioeconomic status and from marginalized groups are at increased risk of experiencing SGBV as a result of resource extraction (Manning, 2016; Simon and Handl, 2021). These threats to women's safety, health, and livelihoods have "intergenerational impacts on women and can exacerbate a cycle of poverty and vulnerability, making already vulnerable populations prone to further violence" (Simons and Handl, 2021, p. 1).

Structural change brought about by mining industries in or near a community is one of the primary contributing factors to SGBV (Jenkins, 2014 and Kotsadam et al., 2017 cited by Atim et al., 2020). Communities with histories of colonization - like those in the Bahamas - are at increased risk of SGBV from societal and structural change that perpetuates and exacerbates colonial legacies (Hettinga and Dean, 2023). These legacies include patriarchal power structures and subordination of women rooted in sexism and structural gender inequality (Atim et al., 2020; Manning, 2016; Simons, 2017; Simons and Handl, 2021). Resulting inequalities women may face include poverty, healthcare and educational disparities, and increased violence (Simons, 2017). Scholars agree that the hypermasculine and male-dominated nature of these industries, often in isolated locations, contributes to SGBV against women (IFC, 2018 and Jenkins, 2014 cited by Atim et al., 2020; Simons and Handl, 2021). Such SGBV is often further operationalized as a tool to concentrate economic resources in the hands of men to maintain patriarchal norms (Atim et al., 2020). Excluding women from consultation processes (Atim et al., 2020), maintaining low numbers of women in high-tier positions (Lauwo, 2016 cited by Atim et al., 2020), and an overall industry workforce of less than 5-10% women (Eftime et al., 2009 cited by Atim et al., 2020) ensures these systems are perpetuated.

Host and fenceline communities near mining operations may experience several kinds of structural transitions. Studies show that there is a positive relationship between community proximity to the mine site, structural change, and SGBV (Cane et al., 2014 and Atim et al., 2020). Many large scale mining projects require more workers than are available in the immediate surrounding area (Edwards, 2019 cited by Hettinga and Dean, 2023). This results in large influxes of male workers from outside of the community moving to mining areas for

economic opportunities (Cane et al., 2014). These workers are often housed in compounds, or 'man camps', on or near the mine site (National Inquiry into Missing and Murdered Indigenous Women and Girls, 2019 cited by Hettinga and Dean, 2023). Man camps have been described as "sexist, disconnected, homophobic, and conducive to levels of hypermasculinity similar to military organizations" (Hettinga and Dean, 2023, p. 4). These camps are usually isolated and far away from workers' homes and other support systems (Gibson et al., 2017 cited by Hettinga and Dean, 2023). Documented effects of these changing community structures include increased substance abuse, gambling behaviors, and sexual violence in and around man camps (Hettinga and Dean, 2023). In addition, multiple studies have shown strong divisions among communities impacted by mining industries, often stemming from problems of inequity (Hettinga and Dean, 2023). Finally, mining may result in forced displacement of communities. Livelihoods and community structures may be radically changed for both the displaced and the host communities (Atim et al., 2020).

One form of SGBV experienced by women living in mining communities is economic disparity. Mining industries not only hire more men than women, but pay women disproportionately low wages and restrict their opportunities for advancement due to gender bias and discrimination (Gibson et al., 2017 cited by Hettinga and Dean, 2023; Measham and Zhang, 2019 cited by Atim et al., 2020; Simons and Handl, 2021). As the local economy grows, women are more likely to become financially dependent on men, especially as housing prices increase and become less affordable to women who are unemployed or making low wages (Amnesty International, 2016 cited by Simons and Handl, 2021). Financial dependency by women on men has been linked to increased risk of violence against women, particularly in domestic contexts (Simons and Handl, 2021).

Households with mine workers are often at risk of experiencing family tensions and breakdowns due to changing routines and family roles associated with work at the mine site (Cane et al., 2014; Hettinga and Dean, 2023). Mine workers are often subject to long shifts and labor-intensive work, resulting in extreme levels of exhaustion and fatigue. A study by Gibson et al. (2017) found that as a result, mine workers were less likely to invest time in childcare, relationships, cultural activities, and household chores (cited by Hettinga and Dean, 2023). Several studies have also cited increased alcohol and drug use among mine workers to cope with the strenuous nature of their work (Simons and Handl, 2019 cited by Simons and Handl, 2021). Exhaustion, work stress, and substance abuse by mine workers can lead to familial conflict that may evolve into various forms of domestic abuse (Cane et al., 2019; Hettinga and Dean, 2023; Simons and Handl, 2021) including physical violence (Cane et al., 2014), psychological abuse (Cane et al., 2014), and financial abuse (Bond and Quinlan, 2018 cited by Hettinga and Dean, 2023). Victims living in communities without support systems or with inaccessible support systems (i.e., too costly) are more likely to remain in abusive situations (Wilcox et al., 2016 cited by Hettinga and Dean, 2023). Gibson et al. (2017) also reported that among Indigenous communities, women and children living in communities geographically closer to resource extractive projects were more likely to experience domestic violence (cited by Hettinga and Dean, 2023).

Many women who work in mining industries experience sexual assault and harrassment in the workplace (Bond and Quinlan, 2018 and Manning et al., 2018 cited by Hettinga and Dean, 2023; Atim et al., 2020; Simons and Handl, 2021). A study by Kaggwa (2019) in South Africa found that 31% of women miners reported abuse at the workplace in a survey (cited by Atim et al., 2020). Another study among female Inuit mine workers reported that 50% of the respondents were concerned about sexual assault occurring in the workplace (Nightingale et al., 2017 cited by Hettinga and Dean, 2023). Paaktuutit Inuit Women of Canada (2021) found that 50% of Inuit women experienced sexual violence in the workplace including unwanted touching, stalking, and voyeurism

(cited by Hettinga and Dean, 2023). Another woman in South Africa reported mining companies in the area encouraging and accepting sexual bribes from women in exchange for employment and promotion (Atim et al., 2020).

Sexual violence is a problem in mining communities even among women and girls who do not work in the mines. According to Adamson (2017), "Sexual violence and sex crimes are the dirty little secrets of the global [extractive] booms" (p. 25, cited by Hettinga and Dean, 2023, p. 8). Increased sexual violence against women and girls in mining communities is largely as a result of an influx of male workers associated with large scale mining (Simons and Handl, 2021; UNICEF, 2015 cited by Atim et al., 2020). Young girls are especially vulnerable targets, with increased instances of child pregnancy resulting from sexual assault in communities near mining operations (UNICEF, 2015 cited by Atim et al., 2020). Cane et al. (2014) reported that in some cases, teenage girls were sexually assaulted after being given alcohol by mine workers. Many are threatened or paid not to speak up. Such risks are increased along haul roads (UNICEF, 2015 cited by Atim et al., 2020). This is a potential concern as North Andros High School is within just a few kilometers of the proposed quarries and haul roads. In Porgera alone, over 100 women living near a mine reported experiencing sexual violence from mine workers, and security personnel in particular (IHRC and CHRGJ, 2009 cited by Manning, 2016). Simons and Handl (2021) likewise found cases of rape and gangrape among women and girls by mine security personnel.

Another form of sexual violence associated with large scale mining - sex trafficking - was referred to as "an issue of grave concern" by the United States Department of State (2017, p.1). Sex trafficking of women and girls has been recorded near mines in Canada, Colombia, Bolivia, Peru, Guyana, the United States, Senegal, and Madagascar - among other countries - and is especially prevalent in remote areas (US Department of State, 2017). Women and girls in these communities experiencing poverty and living in close proximity to man camps are more vulnerable to trafficking (Manning et al., 2018 cited by Hettinga and Dean, 2023). In order to make a liveable wage in the wake of mining booms that women often do not benefit from like their male counterparts, many women are forced to engage in "survival sex" (Tosh and Gislason, 2016 cited by Hettinga and Dean, 2023).

Environmental Contamination (Air, Water, Soil)

A variety of human health problems can arise from environmental contamination of water, air, and soil. Air pollution has been explicitly addressed in the prior section on air quality. Adverse impacts of environmental contamination from limestone mining to soil and water are covered in more detail in the following sections with respect to future food and water security in North Andros. For these reasons, this section will focus on human health impacts due to consumption of contaminated food and water from limestone mining operations. Though limestone mining does not generally result in the production of extremely toxic substances - like acid mine drainage associated with mining of coal and metals - the contaminants it introduces to the environment presents its own range of potential health problems to humans.

As discussed in prior sections, limestone mining can negatively affect water quality by elevating pH, total dissolved solids (TDS), hardness, calcium, and sulphate in nearby water sources (Lamare and Singh, 2016). Additionally, oil and gas spills from mining equipment into nearby water bodies and soils are not uncommon. For Andros, at-risk water bodies include the freshwater lens, tidal creeks, blue holes, and coastal waters, all of which humans use for various purposes from recreation to consumption. Nartey et al. (2012) found that

limestone quarrying processes in Ghana resulted in waste encroachment on to agricultural land, pollution of streams relied on for drinking water, loss of biodiversity and thus food sources, crop destruction, and unclean rainwater locals harvested for drinking (cited by Lamare and Singh, 2016). Lamare and Singh (2016) also found that some water bodies near a limestone mine in India were unfit for human drinking and use throughout the year (p. 96). Water contamination is a human health issue not only due to direct human consumption and exposure, but due to bioaccumulation of contaminants in aquatic and marine animals that humans rely on as a food source (i.e., fish). The same concerns are true of soil and air pollutants that may bioaccumulate in and on terrestrial plants and animals that locals rely on for food.

Water with a pH greater than 8 is considered alkaline. Not enough research has been done to make definitive claims about the health impacts of alkaline water. While some sources claim alkaline water has health-boosting properties, other studies warn against consuming alkaline water regularly. According to the Henry Ford Health System, drinking alkaline water regularly can alter blood pH and thus alter kidney and digestive functions (Castaneda, 2022). If blood pH remains alkaline, a person may experience symptoms like diarrhea, fatigue, and vomiting. Alkaline water with a pH greater than 8.5 may also be accompanied by water hardness, or a high presence of calcium and magnesium. According to the WHO, hard water consumption produces no known adverse health effects and some researchers even argue increased water hardness can improve health by increasing calcium and magnesium in the diet (Galan et al., 2002 cited by Sengupta, 2013). A literature review by Sengupta (2013) reported many studies that affirm these claims, but also described studies that found potential harmful impacts of hard water consumption. For example, two studies in Japan (Hara et al., 1984 and Kuriki and Tajima, 2006) found possible associations between hard drinking water and colon cancer risk (cited by Sengupta, 2013). Additional studies have found links between hard water and skin conditions like eczema and atopic dermatitis (Miyake et al., 2004 cited by Sengupta, 2013). Some studies have also found increased cases of infertility, reproductive failure, and birth complications in hard water regions of India, likely associated with excess intake of calcium (Chandra et al., 2012, Dutta et al., n.d., and Sengupta et al., 2010 cited by Sengupta, 2013). With respect to sulphate contaminants in water, a 2004 World Health Organization (WHO) report found little evidence of adverse health effects resulting from sulphate consumption in water. However, consumption of drinking water containing greater than 600 mg/L sulphate has been linked to catharsis in humans (US EPA, 1985 cited by WHO, 2004). Dehydration has also been associated with consumption of magnesium and sodium sulphates (Fingl, 1980 cited by WHO, 2004). In concentrations greater than 750 mg/L, sulphate may have laxative effects as well (Esteban et al., 1997 cited by WHO, 2004). These findings were affirmed by a 2016 review of mineral water impacts on human health (Quattrini et al.). Oil and gas contamination in water presents significantly more concerning health effects when in high enough concentrations. According to the Hawaii State Department of Health, drinking petroleum-contaminated water can lead to throat and mouth irritation, as well as digestive issues like upset stomach, cramping, nausea, vomiting, and diarrhea (2016, p. 1). If exposed to skin, water contaminated with petroleum may cause itchiness, rash, and peeling. In extreme cases of mining pollution, some communities have been forced to relocate to safer areas via planned resettlement due (Jenkins, 2014 cited by Atim et al., 2020).

More research is needed specifically on the impacts of bioaccumulation of limestone contaminants in plant and animal-based foods, if any, on human health.

Future Water Security

Water security describes the quantity and quality of water available for human use, environmental demand and economic interests (Global Water Partnership, 2000). Water security on small islands can be compromised by climate change. Increased temperatures and changes in the spatial distribution, frequency and magnitude of precipitation are expected to impact groundwater recharge (Green et al. 2011). Sea level rise will result in inundation and potentially a landward shift of the saltwater interface, particularly on low-lying islands. This would result in a loss of freshwater lens volume, either by a reduction in areal extent and/or a thinning of the lens (Oude Essink, 2001). The severity and frequency of extreme weather, such as drought, hurricanes and heavy rain events, will likely increase with a warming climate. Water demand may also increase with warmer temperatures or changes to land use. The cumulative effect of all of these climate-related stressors puts water security at risk, particularly in settlements along coastlines (Holding and Allen, 2016). Changing demographic patterns and tourism pressure drives more infrastructure development along the coasts, rather than at the traditional inland locations, on many small islands (Cashman et al., 2010, Cashman, 2014).

Future climate in The Bahamas is projected to have less precipitation and higher temperatures - a drier and hotter climate state. Spellman et al. (2021) show that actual evapotranspiration (ETa) is increasing across The Bahamas at a higher rate than global averages, due to increases in temperature and a seasonal shift in precipitation from wet to dry season, ultimately suggesting that freshwater availability is on a negative trajectory. Increased temperatures will also lead to increased evaporation (ET) directly from surface water bodies, and this may lead to further thinning and segmentation of FWLs, ultimately leading to more brackish water conditions. The freshwater lens (FWL) on Andros, however, is a gift of nature. It is the largest FWL in The Bahamas, and because of its large size, it offers greater resilience to climate change impacts compared to the smaller FWLs. Most of The Bahamian islands are long and narrow and therefore do not have thick and extensive FWLs.

If the FWL on North Andros is protected, it can provide a long-term sustainable water resource for Andros Island into the future. Protecting the FWL on Andros could also provide water security for other Bahamian islands; sea level rise due to climate change may all but eliminate freshwater lenses on other islands. The wellfield (i.e. the trench network) on North Andros remains in place and freshwater could be barged to other islands as it once was to New Providence. The freshwater on Andros may be the only viable sustainable source of fresh water throughout The Bahamas in the future.

Sustainable development of The Bahamas is currently challenged by both water provision and energy constraints. While desalinization is the primary means for obtaining fresh water on populated islands, such as New Providence, it is very energy intensive and contributes to greenhouse gas emissions through the burning of fossil fuels (Welsh and Bowleg, 2022). Moreover, energy costs may become prohibitive in the future. Therefore, it makes good economic sense to preserve a freshwater resource that may be invaluable to the future of The Bahamas.

If the FWL on Andros is compromised due to mining operations, it will not recover. The excavations for the two proposed open pits will lead to permanent upconing of the salt water beneath and surrounding the pits. The footprint of impact is extensive (see Figure 14). Importantly, this model did not include evaporation from the open pit (a limitation of the model). Therefore, the model results likely underestimate the upconing impact and

the consequent thinning and segmentation of the FWL. Ultimately, there could be a shift in the hydrologic regime of the northern part of Andros. Even if these pits are infilled once the mine closes, the geological substrate will be permanently damaged. This means that the geological material would be unlikely to support a viable freshwater lens.

The open pits would also represent preferential pathways for the entry of contaminants, such as chemical and pathogens from the surface, or sea water that inundates the area during a storm surge (Holding and Allen, 2016). While the FWL on North Andros was locally impacted by past climate-related extreme events (for example, Hurricane Frances in 2004), it was relatively quick to recover because the wellfield trenches could be pumped out with ease. This would not be the case for two large open pits.

In summary, compromising the quantity and quality of water in the freshwater lens due to mining will lead to the reduced resilience of Andros Island to adapt to changes in climate and economic conditions. Future policy decisions regarding the protection and use of the FWL on Andros Island may have significant implications for the long-term sustainability of the lens.

Future Food Security

Almost one quarter of the population of The Bahamas experience food insecurity, largely due to weak food and agricultural infrastructure and a heavy reliance on imports; nearly 90% of food items are imported (Mutiganda, 2021). Food and agriculture contributed to less than 1% of The Bahamas' GDP in 2018 (Mutiganda, 2021). In May, 2022, the Bahamian government announced several initiatives, including increased funding, to bolster agriculture and increase food security in The Bahamas. The Prime Minister stated, "The more we are able to feed ourselves, the better we can withstand external shocks in international markets, and ensure that good, healthy, affordable food choices are always available for our people" (Scott, 2022). As climate change destabilizes food systems, it is all the more important to have local, sustainable agriculture and fisheries.

A major challenge for agriculture in The Bahamas is limited freshwater resources for irrigation. Andros has the largest percent of agricultural land in The Bahamas. Agricultural areas are concentrated around the settlements of San Andros and Bahamas Agricultural Research Community (BARC). The majority of farms use irrigation from private wells on site. These private wells tap into the FWL. If the FWL is compromised, the water may become brackish and unsuitable for agriculture. With such a limited agricultural sector in The Bahamas and growing food insecurity, it is paramount that the freshwater resources of Andros be protected into the future to support potential growth of the agricultural sector.

In addition to limited freshwater availability, agricultural capacity and fisheries are threatened by the impacts of limestone dust on plant, soil, water, and animal health. Particle and gas emissions from quarrying operations can eventually settle on soil and vegetation, and in nearby water bodies. Alkaline limestone dust can raise soil pH, which can alter and even stop growth of sensitive plant species (Farmer 1993b cited by Akanda and Ifelola, 2011). Additionally, excess calcium specifically can lead to nutrient deficiencies in the soil which is detrimental to healthy growth of plants and specifically, farm crops (Ryan and Matar, 1992 cited by Akande and Ifelola, 2011; US EPA, 2022). Nutrient balance in coastal waters and inland water bodies can also be altered, impacting aquatic and marine life that locals may depend on for food. If approved, quarrying may hinder Andros' efforts to explore subsistence agricultural efforts. This will inevitably tighten the hold of a cash-based economy on Andros, disrupting rich and sustainable sociocultural practices on the island.

Blasting and lowering of the water table have negative consequences for fisheries as well. On Grand Bahama, locals have reported fish die-offs following blasting events (Stimpson, 2022). Lowering of the water table at Bahama Rock has also threatened local fishing. According to one local, an area once called "Fishing Hole Road" is no longer suitable for fishing and adds that the nearest place worth fishing is a 32 km drive away (Stimpson, 2022). This is especially concerning for fishing guides whose livelihoods depend on the ability to bring in a good catch, and for locals who depend on fishing for food.

Sustainable and Climate-Prepared Economy

The Bahamas are a high-risk area for climate change (Bethel et al., 2021). By preserving blue carbon ecosystems (i.e., mangroves) and designating protected areas, the Bahamas may be eligible for carbon credits, and will safeguard food sustainability for future generations. By 2030, the global demand for carbon credits is projected to be worth $50 billion, with blue carbon credits accounting for a "significant portion" of that amount (Johnston, 2021). Blue carbon ecosystems are particularly efficient at carbon sequestration and protecting biodiversity, both of which are critical for the health of Andros. Mangroves like those on Andros are unique in this respect (Figure 31). According to Pidgeon (2021), "mangroves have been estimated to prevent more than $65 billion in property damages and reduce flood risk to some 15 million people every year, with overall ecosystem service benefits estimated to fall between $462 billion and $798 billion per year." Studies have also shown that the benefits of mangrove conservation may exceed the cost by three times (Pidgeon, 2021). Additionally, 2.6 km^2 of mangrove can store as much carbon as the annual output of 90,000 cars (Pidgeon, 2021), and thus any reduction in mangrove habitat could be detrimental to Andros and the global climate. In a 2017 sustainable development study of Andros, Arkema et al. found that under intensive development (i.e., limestone mining and dredging), mangrove loss upward of 200 km^2 - and thus loss of carbon storage - will amount to $550 million in damages from West Side National Park alone. Andros already benefits from the protection, tourism value, and carbon sequestering functions of extensive mangroves and is thus well-positioned to take advantage of a blue carbon economy if those ecosystems are protected. Bethel et al. (2021) also advocate developing renewable energy infrastructure to further support the transition to a blue carbon economy. Efforts like those at BAMSI to develop solar energy are already underway and could contribute to long-term and equitable energy access for Androsians.
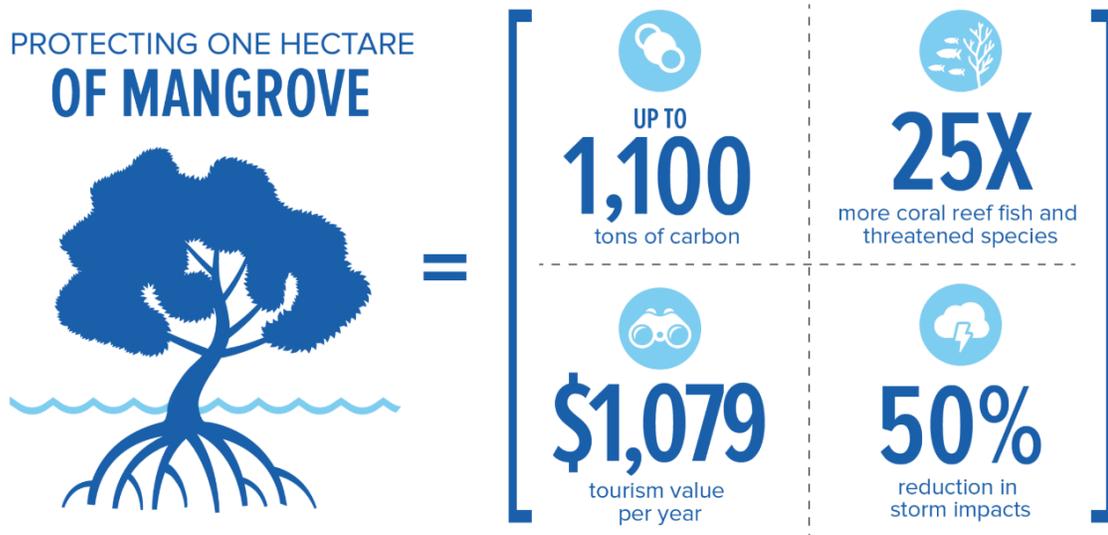
Figure 31. Benefits of protecting mangroves (adapted by Pidgeon, 2021).

In addition to blue carbon, Andros is well-positioned to develop climate-smart fisheries and aquaculture that will in turn support food security for communities across the island. Fisheries account for 1-2% of the Bahamian GDP annually and more importantly, are critical to local economies, cultures, and nutrition (Bahamas Department of Marine Resources, 2011; Bethel et al., 2021). Over a period of twenty years, Queen lobster, Caribbean spiny lobster, and Nassau grouper have generated over $1.4 billion for the Bahamian economy (Sherman et al., 2017 cited by Bethel et al., 2021). Additionally, recreational flats fishing - dependent predominantly on bonefish - accounts for $140 million in contributions to the Bahamian economy annually (Bethel et al., 2021). It is thus critical for the continued success of the fisheries sector of the Bahamian economy to protect the pristine bonefish habitat around Andros, sometimes referred to as the "Bonefish Capital of the World."

This economic sector is at risk, however. According to Béné et al. (2015), "As pressure on ocean ecosystems continues to mount, sustainable management of fishery resources will be critical for meeting nutrition and livelihood needs" (cited by Cusack et al., 2021, p. 8). To adapt to changing climate and ocean conditions, Andros must be responsive to these concerns through proper marine care and stewardship. Marine stewardship and economic growth are not necessarily competing endeavors, if approached correctly. Cusack et al. (2021) propose Alternative Income Generating Activities (AIGAs) to fishing. By aligning marine stewardship - and thus marine natural capital - and economic incentives, Cusack et al. (2021) argue that AIGAs can more efficiently and sustainably use these resources and mitigate pressures to natural fisheries (p. 8). These efforts will only be possible, however, with complementary efforts to sequester carbon and protect water quality and critical reef and mangrove habitat (Bethel et al., 2021). Thus, the blue economy and sustainable fisheries use go hand-in-hand in promoting sustainable economic growth.

Complementary to fisheries is offshore (marine) aquaculture. Campbell et al. (2021) argue that marine aquaculture will be yet another critical conservation step in realizing a blue economy (cited by Bethel et al., 2021). Offshore aquaculture will also present economic benefits for Andros and the Bahamas including

diversification and growth (Belton et al., 2020 cited by Bethel et al., 2021). Based on similar studies by Ahmed and Solomon (2016), we conclude that preserving and expanding climate-smart fisheries and sustainably developing offshore aquaculture will not only economically benefit Andros, but will serve as a step toward increasing food security for Androsians amidst the climate crisis.

Sustainable ecotourism is yet another sustainable economic opportunity Andros and the Bahamas stand to benefit from long-term. As of 2020, the tourism economy accounted for 45% of the Bahamian GDP, 15% higher than the regional average (Mulder, 2020 and Government of the Bahamas, 2021 cited by Bethel et al., 2021). According to Yusof et al. (2014, cited by Ismail et al., 2021), ecotourism will play a critical role in the realm of environmental sustainability and control of carbon emissions globally. If intensive and environmentally destructive development is allowed, however, ecotourism opportunities will rapidly decrease and may not be salvageable for generations, if at all. Without protected natural areas, sustainable ecotourism - or even sustainable tourism in general - is impossible (Arkema et al., 2017; Ismail et al., 2021). Under an intensive development model on Andros, Arkema et al. (2017) found that all seagrass, coral reefs, and beaches will be at high risk. The same study by Arkema et al. (2017) found that Andros will achieve the highest economic returns when there is a balance between developing infrastructure to attract tourists and taking measures to protect unique ecosystems. Ecotourism is thus best achieved when the environment and local communities are cared for and meaningfully considered in decision-making (Arkema et al., 2017; Maciejewski and Kelly, 2014 cited by Ismail et al., 2021). This allows visitors to experience and appreciate the pristine natural beauty of a place as well as the local culture. Ecotourism has been shown to increase the sense of cultural pride among locals and contribute to cultural revitalization efforts (Stronza et al., 2019). This is undoubtedly a result of the participatory emphasis of ecotourism that empowers local communities to guide decision-making (Stronza et al., 2019). By engaging with the environment and cultural values of a place, tourists are more inclined to learn about and advocate for the protection of these places (Ismail et al., 2021). Sustainable ecotourism has also led to the improvement of local living conditions while also reducing pressure on the surrounding environment (Bethel et al., 2021; Stronza et al., 2019). Ferraro and Hanauer (2014, cited by Stronza et al., 2019) cited several studies documenting increased livelihood diversification among communities living in and near protected areas. Marine protected areas (MPAs) will thus be critical in supporting local conservation efforts, ecotourism, and local economic growth (Ismail et al., 2021; Kough et al., 2019; Stronza et al., 2021). In fact, Kough et al. (2019) recommend expanding MPAs in the Bahamas beyond the legally required 20%. MPAs support the fisheries sector by "restoring the biomass and structure of fish assemblages," and contribute to ecotourism opportunities by maintaining ecosystem services (Ismail et al., 2021, p. 9). Another documented benefit of ecotourism is the protection of endangered species (Stronza et al., 2019), of which Andros is home to several, including the endemic Bahama Oriole and Andros iguana. Additionally, many of the skills required in marine ecotourism jobs overlap with skills required for fishing (Cusack et al., 2021), making many Androsians already employable in this sector. Sustainable ecotourism can thus provide a sustainable route for livelihood diversification without relying on intensive and extractive development that will ultimately have negative long-term implications for the environment and economy (Cusack et al., 2021). According to Brandt and Buckey (2018, cited by Stronza et al., 2019), ecotourism is most effective as a conservation strategy when:

1. A specific forest conservation mechanism is in place, such as a protected area, payment for ecosystem service program, or other conservation pledge;
2. There is a spatial boundary delineating the area governed by the conservation mechanism;
3. Local families receive direct economic benefits; and
4. Community-oriented monitoring and enforcement are strong (p. 237).

By following such a model of ecotourism in Andros, the local community's voice will be centered and empowered, locals will receive sustainable long-term economic benefits, and the unique environment of the island will be protected for present and future generations.

Overall, Andros is a unique place that is well-positioned to lead The Bahamas and other nations in developing a sustainable and climate-prepared economy. As climate change places increasing pressures on island nations, it will be critical to mitigate climate impacts, develop food security infrastructure, and pursue diverse sustainable economic opportunities that empower and support local communities. The rich ecology of Andros presents many such opportunities that can change the social, economic, and environmental trajectory of the island for the better - both for local communities and the planet we all call home - for generations to come. These opportunities will not be attainable, however, if intensive development that will destroy these precious ecosystems and communities is allowed to occur. Moving forward, Andros will benefit most from long-term, diverse, and sustainable economic opportunities, which the proposed mining operation in North Andros cannot offer and will actively threaten.

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