An agent-based modeling approach to household adaptation for flooding and coastal erosion at Channel-Port aux Basque

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ABSTRACT

Climate change poses a significant threat to coastal communities, particularly those reliant on coastal infrastructure. Rising sea levels and increasingly severe weather events endanger coastlines across Canada, a nation with over 243,000 km of coastline. Indigenous communities, with their long history of coastal resource utilization, are especially vulnerable. This study investigates the social, economic, and environmental impacts of coastal erosion and flooding in Channel-Port aux Basques, Newfoundland. Hurricane Fiona's devastating impact on the community in 2022 underscores the urgency of adaptation strategies. The research employed a multi-pronged approach: data analysis from weather and census sources, literature review, and agent-based modeling using NetLogo software. Findings reveal significant social impacts, including displacement, emotional distress, and loss of public spaces. While existing adaptation measures like shoreline armoring offer some protection, their effectiveness in the face of stronger storms and projected sea level rise remains questionable. The agent-based model predicts increased coastal erosion, with households within 8 meters experiencing erosion within the first year at current sea level rise rates. The study recommends developing a comprehensive plan to mitigate coastal erosion risks. Potential solutions include sea walls and promoting sustainable land-use practices that prioritize coastal ecosystems and managed retreat strategies. The research concludes by emphasizing the need for context-specific, participatory adaptation strategies to enhance coastal community resilience in the face of a changing climate.

Introduction

Climate change can seriously impact the survival of communities whose livelihoods rely on coastal infrastructure and fisheries (Hailegiorgis et al., 2018). Unguendoli et al. (2023) intimated that climate change has put several coastal communities under unprecedented strain by altering their resource base without giving them enough time for adaptation. While coastal communities have developed and evolved many adaptation techniques over several generations to survive, Hailegiorgis et al. (2018) are of the view that any change in resources may have a huge impact on even highly esteemed and accepted practices and may result in population relocation as well as other serious humanitarian implications.

According to Nicholls et al. (2007), climate and sea level changes harm coastal regions. Storms render coastal regions particularly vulnerable and place heavy costs on coastal regions (Hawick, 2014). Tropical cyclones affect roughly 120 million people annually, and between 1980 and 2000, tropical cyclones killed about 250,000 people (Malenfant et al., 2022). Nicholls et al. (2007) asserted that through the twentieth century, global sea level rise contributed to increasing coastal flooding, erosion, and ecosystem losses, although with significant local and regional heterogeneity owing to other reasons such as coastal dynamic action. Rising temperatures have resulted in the loss of sea ice, thawing of permafrost, accompanying coastal erosion, and more frequent coral bleaching and death since the late twentieth century (Nicolls et al, 2007).

Canada is a coastline country (Davidson-Arnott & Ollerhead, 2011). Except for Alberta and Saskatchewan, all provinces and territories share nearly 243,000 km of coastline (Lemmen et al., 2016). Indigenous peoples have been living along Canada's coasts and utilizing coastal resources for thousands of years (Catto, 2011), and many First Nation, Métis, and Inuit communities still maintain strong links to the shore (Lemmen et al., 2016). Almost 6.5 million Canadians live near the coastlines today, and more than $400 billion in commodities are exported through Canadian ports each year (Atkinson et al., 2016). On the other hand, Lemmen et al. (2016) noted that Canada and its coastal regions are vulnerable to a wide range of storm types and consequences. Strong winds are particularly dangerous in coastal areas since they cause devastating waves and storm surges that lead to coastal erosion. Malenfant et al. (2022) asserted that coastal flooding has been extensive, contributing to the high degree of sea-ice impacts and resulting in record-setting high-water levels in sections of Prince Edward Island, southeastern New Brunswick, Nova Scotia, and Newfoundland.

In the Atlantic region of Canada, coastal erosion endangers the coastline of the province of Newfoundland (Catto, 2011). This has put the towns and cities that depend on coastal infrastructure and activities in danger (Hawick, 2014). Malenfant et al. (2022) added that in addition to reducing social and economic prospects, coastal erosion can destroy infrastructure and property and the extinction of ecosystems. Climate change is making the issue worse on the coast of Newfoundland; therefore, finding a solution in the area is essential. This research paper examines climate adaptation and coastal erosion considering the Southwestern coast of Newfoundland, specifically Channel-Port aux Basques.

Background

Coastal erosion is a big challenge for the community of Channel-Port aux Basques. Channel-Port aux Basques is situated in Newfoundland, which is in Canada's northern Atlantic region, as seen in the map below.

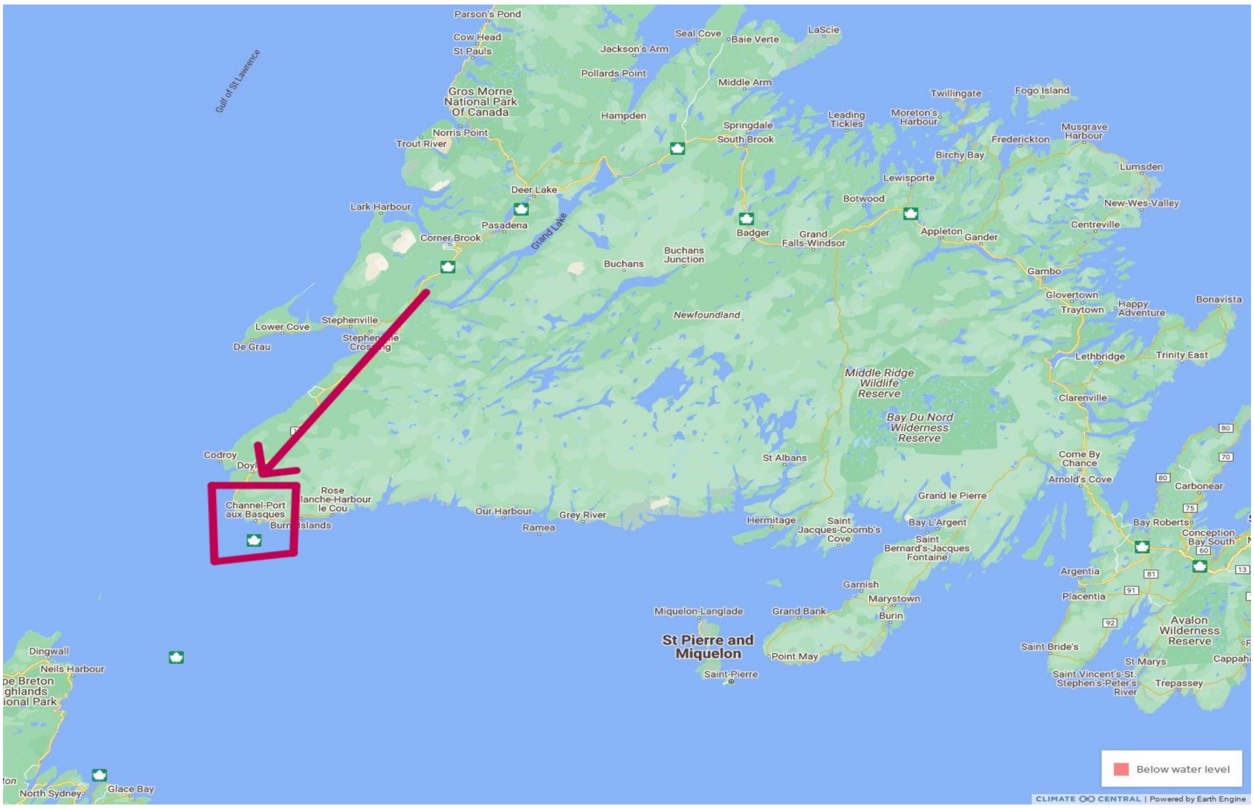

Figure 1: Map of Newfoundland showing the location of Channel-Port aux Basques (Source: Climate Central, n.d)

Like other provinces situated along Canada's coast, Newfoundland's coast is also affected by increasing sea levels, harsh weather events, and ocean acidification. For example, the *Canadian Broadcasting Corporation* (CBC, 2022) reported that in September 2022, several homes were washed away, and many residents were displaced at Channel-Port aux Basques after storm Fiona barreled through this small community in Newfoundland. Malenfant et al. (2022) noted that these concerns have contributed to the acceleration of coastal erosion, which has inflicted considerable harm to the region's infrastructure, property, and ecosystems. Coastal erosion in Newfoundland is a multifaceted issue requiring a transdisciplinary approach. It affects various sectors, including coastal infrastructure, natural resources, and the economy as a whole (Atkinson et al., 2016). Furthermore, Catto (2011) pointed out that the region's coastal infrastructure, including ports, harbors, and roads, is critical to the local economy and the overall well-being of people in this province. Catto (2011) added that the loss of such infrastructure due to coastal erosion can result in significant economic losses and social and environmental damage.

Adding to the economic and social impacts of coastal erosion, the natural resources of Newfoundland, including its diverse marine and terrestrial ecosystems, are also at risk. Coastal erosion leads to habitat loss, fragmentation, and degradation, affecting the region's flora and fauna (Batterson & Liverson, 2010). These ecological changes can, in turn, impact the local fishing and tourism industries, which rely heavily on the region's natural resources (Lemmen et al., 2016).

Adapting to the impacts of coastal erosion and climate change is essential for Channel-Port aux Basques' future resilience and sustainability. Developing and implementing effective adaptation strategies can mitigate the negative impacts of coastal erosion, preserve infrastructure and natural resources, and promote social and economic well-being. This includes using technological innovations, such as agent-based models and simulation, and community-based approaches that engage local communities in planning and implementing adaptation strategies. Therefore, the topic of climate adaptation and coastal erosion in Newfoundland is very complex and pressing, requiring urgent attention. The community's vulnerability to coastal erosion and the impacts of climate change highlights the need for adaptation strategies that are comprehensive, effective, and sustainable. The development and implementation of such strategies will be important for Channel-Port aux Basques' resilience and ability to adapt to future challenges.

Castro et al. (2020) opined that agent-based models (ABMs) have lately received widespread use in the field of climate mitigation initiatives since they provide a more realistic account of micro behavior than classic climate policy models by allowing for agent heterogeneity, constrained rationality, and nonmarket interactions across social networks. This enables the analysis of a broader spectrum of policies. Agent-based modeling will, therefore, be used to inform and optimize climate adaptation methods for Channel-Port aux Basques' coastal erosion management.

Research objectives

This research paper aimed to assess how agent-based modeling can be utilized to inform and optimize climate adaptation methods for coastal erosion management at Channel-Port aux Basques. This research will achieve the following objectives:

i. Evaluate coastal erosion's social, economic, and environmental impacts on Channel-Port aux Basques.
ii. Investigate the current climate adaption techniques being used to manage the physical impact of erosion
iii. Examine how successful these climate adaptation techniques have been in reducing the effects of coastal erosion.
iv. Determine if agent-based modeling can be useful for forecasting the effects of coastal erosion and climate adaptation at Channel-Port aux Basques.

Literature Review

According to Pearson (2023), the coastline surrounding the Atlantic Ocean is receding as much as 18 feet a year. The United States Environmental Protection Agency (EPA, 2022) asserted that roughly 20 square miles of dry land and wetland were converted to open water along the Atlantic coast between 1996 and 2011. Pearson (2023) gives evidence of this sea level rise by citing an example of a fishing town in Brazil being engulfed by the rising Atlantic Ocean, displacing hundreds of families. Like Channel-Port aux Basques, the town called Barra dos Coqueiros, located on the northeastern coast of Brazil, has been facing the impacts of sea-level rise and erosion for years. The situation has worsened in recent years, with the ocean reaching some homes and businesses during high tides. Local authorities have been working on solutions to protect the town, including building a sea wall, but the project has faced delays and funding issues. The residents are now calling for urgent action to save their homes and livelihoods (Pearson, 2023).

The EPA (2022) noted that the coast of the Atlantic Ocean is experiencing land loss due to a combination of factors such as sea-level rise, erosion, and human activity. This phenomenon is affecting several states, from the United States to Atlantic Canada, and has severe consequences for local communities, infrastructure, and ecosystems. The EPA (2022) further noted that coastal erosion is a natural process that has been accelerated by human activities such as construction, damming, and sand mining. Rising sea levels exacerbate the problem, causing more frequent and severe flooding and erosion (Pearson, 2023). The impacts are particularly severe for vulnerable populations such as Indigenous communities and low-income households. Communities are implementing various strategies to mitigate and adapt to the impacts of coastal erosion, including beach nourishment, wetland restoration, and managed retreats. However, these measures can be costly and require long-term planning and collaboration.

Coastal erosion occurs when coastal landmasses are eroded by water, wind, and waves (Unguendoli et al., 2023). The average rate of erosion is about 4 feet per year. However, some sites, like islands in the southwestern part of Newfoundland, can lose up to 25 – 50 feet of shoreline every year (Catto, 2011). Malenfant et al. (2022) opined that climate change is greatly accelerating this phenomenon. Hence, global sea levels are expected to rise 3-6 vertical feet by the year 2100.

Davidson-Arnott and Ollerhead (2011) asserted that coastal erosion is a natural process that involves the disintegration (or "weathering") of rock and silt near the bank of the sea, both above and below the surface of the sea. Luther (2013) posited that this natural process in coastal locations is triggered by a variety of variables that can have various impacts on shorelines. Wind, water, and ice are the most common drivers of coastal erosion, with wave action near the beach having the most severe consequences. Erosion predominates in locations where sedimentary material is sparse and waves transport material away from the coast. Coastal erosion occurs in Atlantic Canada as a result of wave action and, to a lesser extent, tidal action, wind, storm surge, ice, rain, and surface runoff (Catto, 2011). The rates of erosion and deposition vary depending on the location of the shoreline. Changes in climatic conditions, sea level, and human actions can also have an impact on erosion and deposition rates and can affect the rate of coastal change (Marchand, 2010).

Coastal erosion causes the shoreline to drift landward when cliffs retreat or beach and dune systems "migrate" (Nicholls et al., 2007). Furthermore, dunes and salt marshes may vanish entirely in certain areas, while new depositional characteristics may arise in others (Manes et al., 2023). Luther (2013) opined that landward migration of the coastline frequently disrupts human operations by endangering roads, houses, and other coastal infrastructure used for fishing, agriculture, and transit. It may also cause changes in coastal ecosystems (Unguendoli et al., 2023). Similarly, deposition and seaward displacement of the coastline may pose new obstacles to human activities as well as changes to the natural ecosystem (Atkinson et al., 2016).

According to Locatelli et al. (2020), climate change is predicted to cause a rise in sea level and a decrease in sea ice, increasing the rates of erosion in many sites along our coasts. However, different coasts will be affected to differing degrees. In perspective, the dynamic beach and barrier systems that border most of Atlantic Canada's coastline will also be impacted (Catto, 2011). Both Catto (2011) and (Malenfant et al., 2022) agree that increasing sea levels and more violent storm activity may force beaches and barriers to move or perhaps vanish as silt is transported from one region to another. Atkinson et al. (2016) added that salt marshes will also be influenced by climate change when they become swamped by increasing sea levels; these places are likely to move farther inland as long as there is enough space and sediment supply. While it is impossible to predict the exact rates at which sea levels will rise and shorelines will erode, both rates are guaranteed to rise (Curtis, 2020).

Manes et al. (2023) mentioned that a mixture of four distinct actions largely causes coastal erosion. The first type of action is hydraulic action, which involves the direct impact of waves on a cliff, trapping and pressurizing air in cracks and fissures, causing fractures to develop and finally tearing apart the cliff face. The second is attrition, which happens when enormous boulders clash with other rocks, transforming them into pebbles and eventually converting them into sand. Abrasion is the third cause of coastal erosion. Manes et al. (2023) further noted that abrasion is often referred to as "sandpapering," it occurs when a material like sand wears away a coastal surface like bedrock. The fourth cause of coastal erosion is known as *dissolution*, which is a chemical process in which seawater dissolves minerals in coastal landmasses.

Waves and storms, sea-level rise, and human meddling all have an impact on coastal stability. Luther (2013) contended that the capacity of a wave to cause erosion is ultimately determined by wind climate. Hence, increased wind speed can trigger an increase in wave energy (Curtis, 2020). Furthermore, increased wave energy and, consequently, increased wavelength allow the wave to transport bigger particulates that disrupt and shift greater amounts of silt. Storm surges, which expose higher land elevations to more intense wave conditions, might accelerate the overall erosion consequences of waves. The timing, trajectory, climatic conditions, local peculiarities of the location, and the angle at which waves hit the beach all have an impact on the total impact of a storm (Luther, 2013).

Methods

According to the Municipal Plan (Municipal and Provincial Affairs, 2019), the weather patterns are changing in the province of Newfoundland and Labrador, and severe weather occurrences – abnormally high winds, storm surges, and heavy precipitation, among others – are now more frequent and severe than they were previously. Channel-Port aux Basques is a town in Newfoundland's extreme southwestern corner, near the western extremity of the Cabot Strait. The town has a Marine Atlantic ferry port and is the western terminus of Newfoundland and Labrador Road 1 (Trans-Canada Highway). The town was incorporated in 1945. The town had a population of 4067 according to the 2016 census and 3547 according to the 2021 population census, implying a 12% decrease in population size between 2016 and 2021. Port aux Basques is the oldest of the collection of towns that make up the present-day town, which consists of Port aux Basques, Channel, Grand Bay, and Mouse Island. In the Mi'kmaq language, the town is called "Siinalk" (MapNall, n.d).

CBC (2022) reported that Hurricane Fiona caused a partial evacuation of the town in September 2022. Around 100 residences were allegedly washed away by the wind and storm surge in Newfoundland, with the majority of the homes being from Channel-Port aux Basques. Several residents of the town reported that it was the worst storm they had ever seen, and it was a life-changing experience for them. The town proclaimed a state of emergency on September 24, 2022 (CBC, 2022).

Channel-Port aux Basques has significant seasonal lag and is frigid for its latitude. This is because the Icelandic Low and the Labrador Current impact it, resulting in a unique mix of cold and snowy winters at its seacoast at 47°N (Government of Newfoundland and Labrador, n.d). The chilly waters delay the warmup in the summer, while westerly winds from the interior of Canada are quite cold in the winter, further delaying the warming of the water.

As a result, August is noticeably warmer than July, and September is more than 2 degrees Celsius (3.6 degrees Fahrenheit) warmer than June. Winter precipitation frequently falls as snow, resulting in a large yearly yield. However, rainfall is also prevalent even in the coldest months of February, lowering the snow cover to an average of about 55 cm (22 in) at its annual peak.

The coastal roads of Channel-Port aux Basques are projected to go underwater by 2030 due to the rate at which the coast of the town is being washed away (CBC, 2022). Figure 4 below is an overview of Channel-Port aux Basques. It shows the areas in the community that are estimated to go below sea level and the areas in the community prone to flooding and coastal erosion.

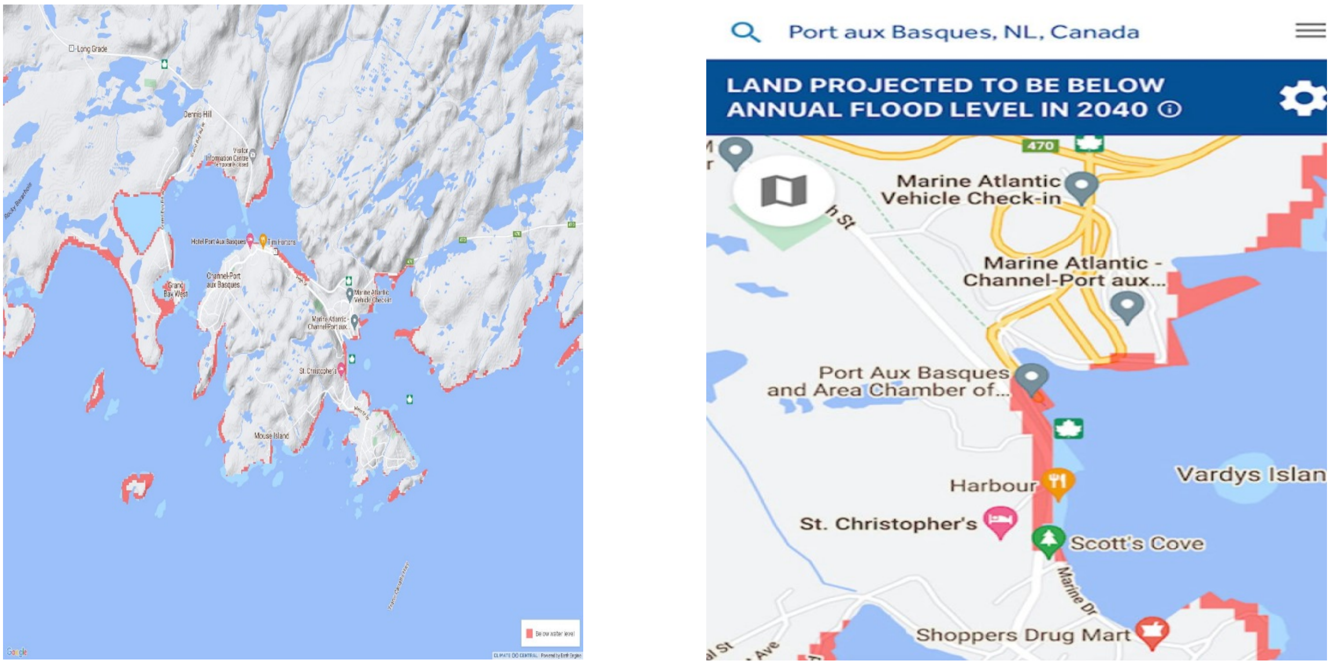

Figure 2: Overview of the case study areas. Left: the case study area lying below sea level. Right: The case study area that is prone to flooding and coastal erosion (Source: [Climate Central, n.d]).

The Municipal Plan (Municipal & Provincial Affairs, 2019, p. 26) forecasted a gradual rise in the mean sea level, which will increase the impact of storms and floods at Channel-Port aux Basques. Coastal flooding in this community is often near the shoreline and nearby low-lying areas. Sustained high winds combined with storm surges have the potential to cause damage along the coast, adversely impacting municipal infrastructure and infrastructure used to deliver electricity and communications services to the public. In January 2000, a major storm surge caused significant damage to southeasterly facing portions of the town, such as Mouse Island and Channel. Most of the damage seems to have occurred up to 8 meters above sea level elevation, with some damage occurring up to 12 meters elevation. To adapt to changing weather conditions, the town has found it prudent to recognize and identify areas that may be susceptible to flooding and to curtail the development of emergency services and structures housing large numbers of people or vulnerable populations in low-lying areas below the 4-meter elevation contour.

Research design

This research utilized an in-depth literature review to comprehensively understand coastal erosion and flooding at Port aux Basques. This approach proved valuable as it allowed for systematically examining existing knowledge on the topic, offering a broader and more nuanced perspective than a single case study. This review, therefore, focused on the town of Channel-Port aux Basques in Newfoundland, Canada.

Data Collection

The first part of the data for this research paper was gathered from available weather and population census data from Climate Central (n.d), Statistics Canada (2016), Statistics Canada (2021), and the Government of Newfoundland Climate Data website (Government of Newfoundland, n.d). This data was used to develop the agent-based model (ABM) and validate the model's output. ABMs require proper handling of uncertainty. Therefore, simulation of the framework based on quantitative uncertainty and sensitivity analyses is necessary to build ABMs that serve two purposes: an exploration of the outcome space to simulate low-probability but high-consequence events that may have significant policy implications and an explanation of model behavior to describe the system with higher accuracy (Ligmann-Zielinska et al., 2014). Uncertainties were incorporated into the model when the simulation was being done. The output was analyzed using mathematics to identify trends and patterns.

In addition, a literature review was conducted to gather the data for this paper. To do this, the Municipal Plan of Channel-Port aux Basques, existing literature, and online sources were consulted to gather data for the research paper. This data included information on coastal erosion rates, storm surge data, sea level rise data, and other relevant environmental data.

The data gathered from the literature search was then analyzed to understand this topic. The results of the agent-based model were then compared to the seven steps to assessing climate change vulnerability (Government of Newfoundland, 2012) and other qualitative news reports and qualitative data to validate the model's output and to provide a more complete understanding of the issue. Using different approaches, this research methodology provided a more complete understanding of climate adaptation and coastal erosion at Channel-Port aux Basques. The agent-based modeling approach helped to develop scenarios that helped to identify potential adaptation strategies for the town. At the same time, the qualitative data provided insight into the social and economic impacts of coastal erosion on the community. This data was used to inform the model and to make key considerations as part of the community's vulnerability assessment and adaptation choices.

Results and discussions

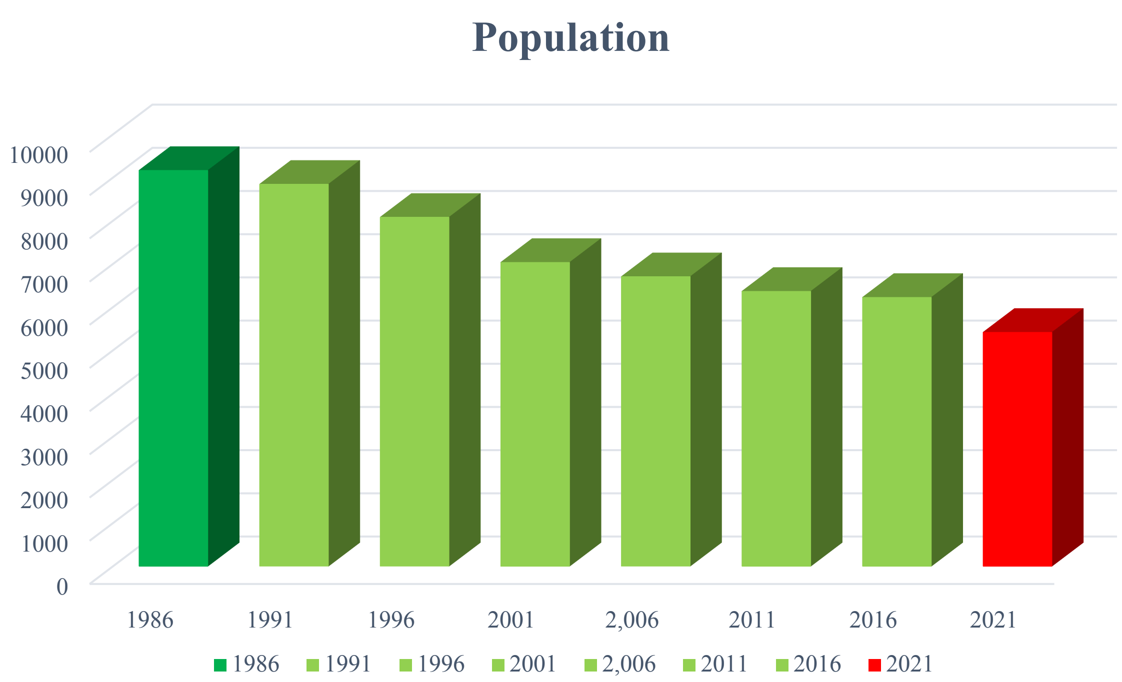

Figure 3: Population of Channel-Port aux Basques from 1986 – 2021 (Data source: Newfoundland and Labrador Statistics Agency, 2021)

Figure 3 shows the population data of Channel-Port aux Basques from 1986 to 2021. It is evident from the figures that the community's population has steadily declined from 1986 to 2021. The Community

Account Unit of the Newfoundland and Labrador Statistics Agency (NL Statistics Agency, 2021) revealed that the population of Channel-Port aux Basques in 2021 was 4,055. On the other hand, Statistics Canada (2021) stated that Channel-Port aux Basques' population was 4061 in 2016 and 3547 in 2021. The reason for the different figures was unclear by either Statistics Canada (2021) or the Newfoundland and Labrador Statistics Agency (2021). However, both organizations' data show that there has been a 12.5% decrease in population size from 2016 to 2021 (4,055 in 2021, down from 4,635, according to Newfoundland and Labrador Statistics Agency, 2021). The data from the Community Accounts Unit of the Newfoundland and Labrador Statistics Agency (2021) depicted that from 2016 to 2021, the province's population decreased by 1.8% (510,550 in 2021, down from 519,715). In 2021, the median age in Channel-Port aux Basques was 54. The median age in Newfoundland and Labrador in 2021 was 48 (Newfoundland and Labrador Statistics Agency, 2021).

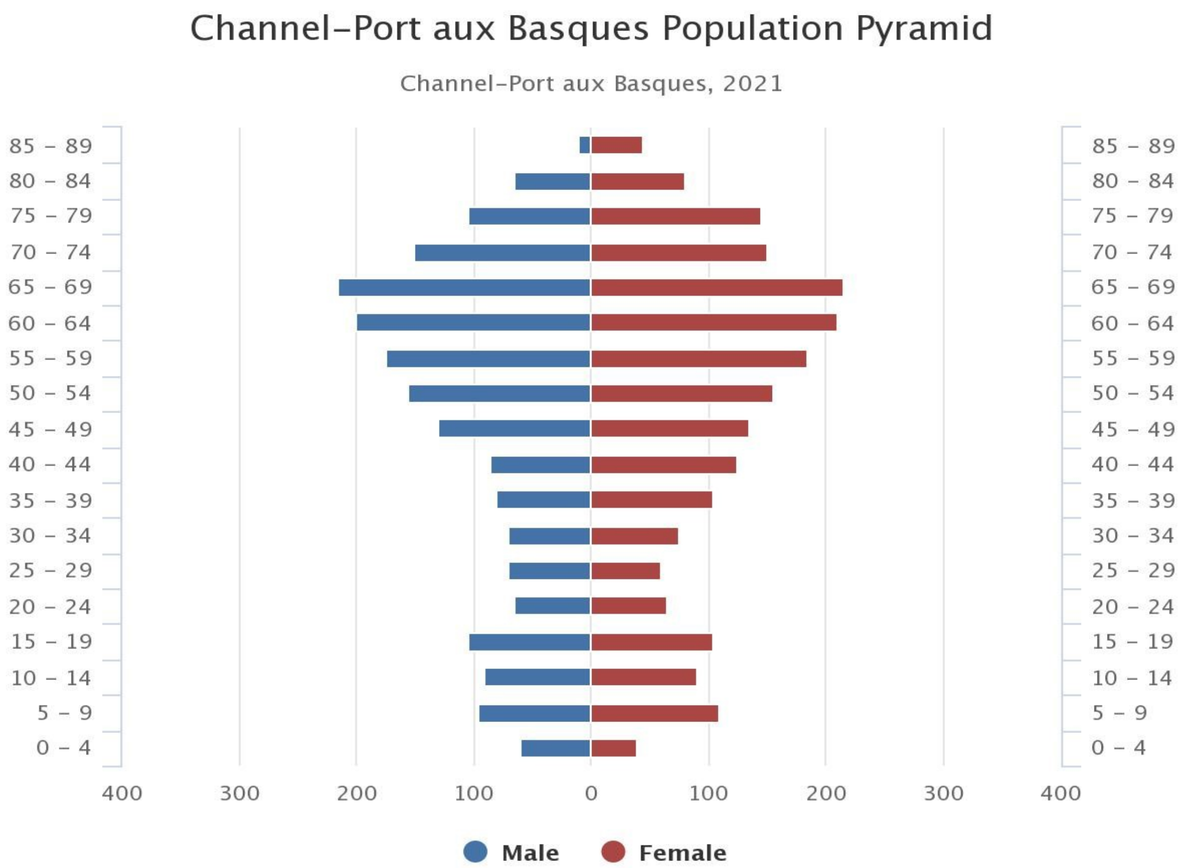

Figure 4: Channel-Port aux Basques 2021 population pyramid (Data source: Newfoundland and Labrador Statistical Agency, 2021)

Figure 4 also shows the 2021 population pyramid of Channel-Port aux Basques from age one to age 89 by 5-year age group and gender. The figure shows that most of Channel-Port aux Basques residents are between the ages of 45 and 84 years. Again, the reason for distribution was not explicit. However, the Newfoundland and Labrador Statistics Agency (2021) indicated that in 2019, the Residual Net Migration for Channel-Port aux Basques was -1.01% (-45 people). In the same year, it was -0.39% (-1,995 people) for the province. Net migration is computed using the residual technique by subtracting the current population from the prior year's population and eliminating the effect of births and deaths on the population. The remainder/residual is the number of persons relocated into or out of the area. Hence, removing births and deaths from the difference, it was clear that the community's population kept dwindling due to migration. This could imply that the community's population is aging, which increases the community's vulnerability to the impact of flooding and coastal erosion. Even though this research paper is not about any particular age or gender group, it is generalized to give a more accurate prediction of the community's vulnerability to the impact of coastal erosion and the need for sustainable adaptation strategies.

Data from the Municipal and Provincial Affairs (2022) revealed that from 1898 to 1988, Channel-Port aux Basques thrived with a bustling, diverse economy stapled with the passenger and freight ferry service, railway, and fisheries. Growth in the town during those ninety (90) years was a sign of the prosperity the three major industries provided. However:

> In 1988, the Newfoundland Railway scheduled the last train departure for the province. The railroad, with its narrow gauge, was deemed inefficient in comparison to commercial road transportation. Channel-Port aux Basques was dealt a major economic setback with the loss of hundreds of jobs. With a small population, these job losses were a setback to the economy of the town (Municipal and Provincial Affairs, 2022, p. 16).

This resulted in a gradual decline in the community's population, which has continued to the present day. The Municipal Plan of Channel-Port aux Basques (Municipal and Provincial Affairs, 2022) showed that the reasons for the overall demographic trends are well known and include declining birth rate, outmigration to other areas in search of employment in one's skill, young people leaving for education and not returning; limited job growth in emerging businesses and institutions, and the recent COVID-19 pandemic as well as hurricane Fiona. In January 2000, more than a decade before Hurricane Fiona, high waves and storm surges struck the community, damaging houses, wharves, and fishing shacks. These factors operate throughout the province's rural areas and vary only in degree. The general trend is that employment and population are concentrated in the larger urban centers (Batterson & Liverman, 2010).

Housing period of construction (2021 Census)

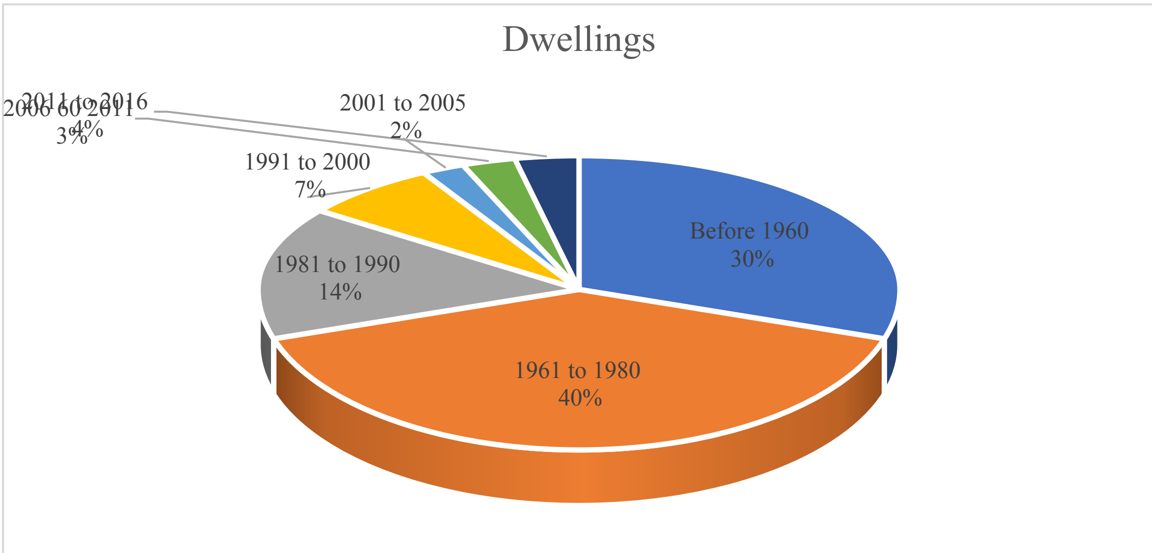

Figure 5: Housing period of construction (Data source: NL Statistics Agency, 2021)

The data obtained from the Newfoundland and Labrador Statistics Agency (2021) depicted that Channel-Port aux Basques had 1,885 homes according to the 2021 Census, down from 2,085 in 2016. Private farms or reserve homes are not considered residences. There were 1,640 detached houses and 115 flats among them. There were 1,265 single-family households, 15 multiple-family homes, and 600 non-family households in total.

Statistics Canada (2021) reported that according to the 2016 Census, 78.2% of residences in Channel-Port aux Basques were owned rather than leased, compared to 76.8% in the province and 67.8% nationally. In 2016, the average monthly shelter cost for owned residences was $743. In 2016, the average monthly shelter cost for owned residences in the province was $984, the average monthly shelter cost paid by renters was $668, and the average monthly shelter cost paid by renters in Ontario was $836 (Statistics Canada, 2021). The 2021 data for this location was not yet available when conducting this research. The Newfoundland and Labrador Statistics Agency (2021) revealed that the people living in Channel-Port aux Basques reported in 2016 that:

- 625 dwellings were constructed before 1960.
- 835 dwellings were constructed between 1961 and 1980.
- 285 dwellings were constructed between 1981 and 1990.
- 145 dwellings were constructed between 1991 and 2000.
- 50 dwellings were constructed between 2001 and 2005.
- 65 dwellings were constructed between 2006 and 2011.
- 80 dwellings were constructed between 2011 and 2016.

This means that only 16% of the houses were constructed between 1991 and 2016, with the majority of the housing being constructed from 1960 to 1990. The Municipal Plan (Municipal and Provincial Affairs, 2022) indicated that the town maintains a storm sewer system that covers 90% of the community. The CBC (2022), however, reported that the town's storm sewers and water lines are old and unusable (with the construction of some parts of the sewer dating as far back as 1898). Therefore, stormwater runoff has been a concern for the town residents. Still, the town's Council has not felt the need to develop and implement a stormwater detention/zero net runoff policy for new development (Municipal and Provincial Affairs, 2022). The findings, therefore, show that the community is vulnerable to storms and erosion.

Sea level rise

Batterson and Liverman (2010) found that a tide gauge near Channel-Port aux Basques showed that the absolute rate of sea-level rise ranges from 2.5 millimeters per year to 3 millimeters per year. According to Batterson and Liverman (2010), this rate of sea level change is general across the shoreline of Newfoundland and Labrador. It is a result of a combination of global factors and local/regional influences. Climate Central (n.d) reported that the current global rate of sea-level rise is estimated at 3mm per year compared to the province's 2.7 mm, based on satellite altimetry and tide gauges. Catto (2011) noted that over the past 50 years, Channel-Port aux Basques has reported a 3.3 mm sea level rise annually. Figure 4 shows the areas at and around Channel-Port aux Basques lying below sea level and areas prone to flooding and coastal erosion, which agrees with the findings of Batterson and Liverman (2010), Catto (2011), and Pearson (2023) that the Atlantic Ocean is seeing a gradual annual increase.

Weather patterns are also changing in Newfoundland and Labrador, and severe weather occurrences such as abnormally high winds, storm surges, and heavy precipitation are now more frequent and severe than they were previously (Provincial and Municipal Affairs, 2022). The province is feeling the impact of climate change. The forecasted gradual rise in the mean sea level increases the impacts of storms (Catto, 2011). Sustained high winds combined with storm surges cause damage along the coast, adversely impacting municipal infrastructure and infrastructure used to deliver electricity and communications services to the public. Both the January 2000 storm surge and 2022 Hurricane Fiona "caused significant damage to the southeasterly facing portions of the town – Mouse Island and Channel-Port aux Basques. Most of the damage occurred up to 8 meters above sea level elevation, with some damage occurring up to 12 meters elevation previously (Provincial and Municipal Affairs, 2022, p. 26). To adapt to changing weather conditions, the town has recognized and identified areas that may be susceptible to flooding and to curtail the development of emergency services and structures housing large numbers of people or vulnerable populations in low-lying areas below the 4 meters elevation contour (Zhai et al., 2014). Based on these findings, the assumption could be made that sea levels will continue to rise. Therefore, planning has to take into consideration crustal adjustment/isostatic response, global changes in sea levels (Batterson & Liverman, 2010), and old infrastructure that may not support the current trend of weather conditions and sea level rise (Locatelli et al., 2020).

Social, economic, and environmental impact of the coastal erosion

Coastal erosion and flooding have had significant social, economic, and environmental impacts on Channel-Port aux Basques. The following social impacts were identified in various literature:

i. The displacement of more than 200 people and the relocation of more than 20 homes and several businesses have caused emotional distress and disconnection for many community residents affected by flooding (CBC, 2022).
ii. Coastal erosion and flooding have also caused physical harm, such as injury and one person's life loss during Hurricane Fiona (CBC, 2022). This risk is very high during extreme weather events.
iii. Blankson (2022) mentioned the loss of beaches, parks, and other public spaces (CBC, 2022) due to erosion and flooding, which has reduced the quality of life for residents and visitors (Atkinson et al., 2016).

Unguendoli et al. (2023) noted that the stress of living in such areas with a high risk of flooding and coastal erosion can lead to mental health issues and anxiety for residents. This is evident at Channel-Port aux Basques. CBC (2022) reported that the community flooded just weeks after Hurricane Fiona, leaving residents in town very stressed and worried.

Aside from the social impacts, flooding and coastal erosion have also had economic impacts on Channel-Port aux Basques; for instance, flooding has damaged or destroyed infrastructure such as roads, bridges, and buildings, resulting in costly repairs and disruptions to transportation and business activities. CTV News (2023) estimated that insured damages resulting from flooding and coastal erosion, including the cost of destruction caused by Hurricane Fiona, are about $660 million. The loss of beaches and waterfront areas has also harmed tourism, a significant contributor to the local economy.

The Municipal Plan (Municipal and Provincial Affairs, 2019) mentioned that coastal erosion has led to the loss of important coastal ecosystems, such as salt marshes and dunes, which provide important habitats for plant and animal species. This agrees with the findings of Nicholls et al. (2007), who found that the rise of global sea level gradually contributes to increasing coastal flooding, erosion, and ecosystem losses. Eroded soil and sediment can also cause damage to marine ecosystems, including coral reefs and seagrass beds (Catto, 2011). Coastal erosion and flooding significantly negatively impact the social, economic, and environmental well-being of Channel-Port aux Basques. The community is, therefore, taking measures to mitigate these impacts.

Current climate adaption techniques being used to manage coastal erosion

Weather-related events impact the physical environment, causing harm to infrastructure, property, cultural sites, and ecologically sensitive places. In rare situations, weather-related difficulties, such as increased precipitation, might endanger individuals and necessitate the evacuation of particular places.

Adaptation measures

The Municipal Plan (Municipal and Provincial Affairs, 2022) mentioned that the land resources of the Channel-Port Aux Basques are being managed per the proposed land uses and the land use policies of the community's Municipal Plan. Residential lands must be zoned Residential (RES) or Residential Medium Density (RMD). Furthermore, the Residential (RES) Zone has been applied to develop older portions of town and newer regions around Grand Bay, where single-family dwellings are and will continue to be the most common residential housing form. The Residential Medium Density (RMD) Zone has also been applied to a relatively small area that is bounded on the northeast and southwest by lands zoned Residential and fronting along Dennis Road, Tavernor Drive, and Smallwood Drive, on the southeast by land occupied by an Environmental Protection waterway and associated wetland, and on the northwest by land also designated Environmental Protection that is the Dennis Pond wetland detention area (Municipal and Provincial Affairs, 2022).

Also, the Residential Medium Density (RMD) Zone has been established to allow for a broader choice of greater-density residential dwelling styles as an allowed use. As a result, where lands are designated Residential (RES), only the following uses are permitted: accessory building; single residence; subsidiary apartment in a single detached dwelling; double dwelling; bed and breakfast; childcare - family; conservation; home office usage; recreational open space; public service; public utility. The town will require non-residential use to be suitably buffered or screened to minimize its impact on nearby residential properties and to mitigate the impact of coastal erosion (Municipal and Provincial Affairs, 2022).

CTV News (2023) revealed that almost six months after Hurricane Fiona wreaked havoc at Channel-Port aux Basques, much effort, funding, and support have gone into helping residents who were affected get back on their feet; hence, only adaptation measures are about not building so close to the shore, leaving behind vulnerable places, and living in more secure, resilient places.

Adaptation Measures of Ocean Choice International

Ocean Choice International CBCL (OCI) Limited conducted a coastal modeling study to investigate the potential impacts of proposed land reclamation for the future Ocean Choice International (OCI, 2020) wharf and cold storage facility at different communities, including Long Pond Harbor in Conception Bay South and Channel-Port aux Basques.

The report (OCI, 2020) shows that shoreline erosion assessment, wave, current, tide gauge monitoring, sediment sampling, bathymetric surveys, and infrastructure /shoreline assessments were done at the field investigation stage. Flood mapping guidelines, municipal climate change action plans, infrastructure planning, and coastal community adaptation tools were implemented at the planning regulatory state. This was, however, not reported in the Municipal Plan. The Municipal and Provincial Affairs (2022) reported that public consultation was done at the first step in the planning process, where the town’s consulting planners carried out basic background information gathering and consulted with members of the Council, staff and residents, and business owners/operators, as well, to aid in building the initial information base needed for adaptation planning. From the literature obtained, the following were found to be the current adaptation techniques being used to manage coastal erosion and flooding at Channel-Port aux Basques:

Managed retreat: This involves moving homes and infrastructure away from the coastline to allow the natural processes of erosion and deposition to occur without damaging buildings or infrastructure (Municipal and Provincial Affairs, 2022; CT News, 2023).

Education and outreach: Residents are being educated about the risks of coastal erosion and how they can protect their homes and property to help them reduce the impact of coastal erosion. The town has held public information sessions to educate the residents (Municipal and Provincial Affairs, 2022).

Monitoring and planning: There is ongoing regular monitoring of the coastline to help identify areas that are at risk of erosion, allowing for proactive planning and implementation of adaptation measures. This is why the town is conducting regular monitoring and developing a Coastal Zone Management Plan through public and private consultation to guide future adaptation efforts (OCI, 2020).

Effectiveness of the current climate adaption techniques

Combating climate change in Newfoundland and Labrador necessitates simultaneous efforts on two fronts: adjusting to inevitable consequences to increase our province's resilience and lowering GHG emissions to avoid harsher impacts in the future (Municipal Affairs and Environment, n.d). Adaptation requires a better knowledge of how climate change will affect the province, raising awareness and capability regarding the consequences for various sectors, and correctly incorporating climate issues into decision-making (Curtis, 2020).

Education and outreach, as well as monitoring planning, were identified as the major adaptation techniques being used to manage coastal erosion. It could, therefore, be that the ongoing education to the residents of the community and the post-Fiona engagement, monitoring, and planning have led to the managed retreat, where homes and infrastructure that are within certain meters of the coastline are being moved to allow the natural processes of erosion and deposition to occur without damaging buildings or infrastructure (Municipal and Provincial Affairs, 2022).

Blankson (2021, p. 62) found that the "major activities undertaken by the town of Channel-Port aux Basques to reduce climate impacts (coastal flooding and shoreline destruction) include the construction of armor stones along the coast and enforcing the town's regulatory tools. The amour stones are large hard rocks usually put along the coast to protect the coast and the surrounding built environment. These rocks protect the coast from eroding by trapping and retaining the sand during heavy wind and rainfall and deflecting wave energy, which can destroy coastal coastlines and properties (Blankson, 2021). Participants who were interviewed by Blankson (2021) at Channel-Port aux Basques stated that they put these big rocks called armor stones along the shoreline to reduce the impact of the waves hitting the shoreline. The participants further noted that the town has employed regulatory tools to manage the impacts of coastal flooding. This is seen in the literature, where OCI (2020) highlighted coastal community adaptation tools in the town as part of the planned, policy, and regulatory measures to manage adaptation.

Another participant in Blankson's (2021) study mentioned zoning and rezoning as an example of regulatory tools used to regulate land use and development in the town. This is done through text amendment and map updating, among others. Again, the town uses the buffer and development permits to control individuals and private businesses from building on prohibited and protected coastal areas. The participant attested that the above-mentioned regulatory tools have provided some developer guidance. Though the armor stones were in place before Hurricane Fiona occurred, the impact of the hurricane was still severe, implying that the armor stones cannot protect the coastline from strong storms.

The assertion could, therefore, be made that the initial adaptation techniques of zoning, educating, and reaching out to the residents close to the coastline, as well as monitoring and planning, have successfully moved residents away from the coastline to avoid the impact of sea level rise. The armor stones are also successful in preventing waves from eroding the coastline. However, there is no data to prove that the armor stones can be a very successful technique to mitigate any coastal erosion and flooding in the future. Since the literature shows that the majority of the residents fall into the category of an aging population and the majority of the homes and infrastructure are old and do not support the current erosion situation, the question remains as to whether the education and managed retreat alone will be the most effective adaptation techniques in the future if the sea level rises higher than what was noted by Catto (2011) and Climate Central (n.d) or any hurricane stronger than Fiona hits the community. On the other hand, since the Municipal Plan mentioned ongoing stakeholder and community engagement and consultations (Municipal and Provincial Affairs, 2022) and OCI (2020) also mentioned risk assessment, stakeholder engagement, and adaptation planning, perhaps more adaptation plans will be laid out after the assessment, monitoring, consultation, and planning have been completed.

Agent-based modeling

In Channel-Port aux Basques, erosion is a significant challenge to the environment and the community's way of life. Agent-based modeling was used to understand how residents of Channel-Port aux Basques can adapt to their environment over time. This modeling approach allowed for the development of a framework for understanding how the population of Channel-Port aux Basques can adapt to coastal erosion and whether this adaptation process can be sustained.

Model environment

The model environment represents the coastal environment of Channel-Port aux Basques and how it adapts over time due to the effects of erosion and flooding. The turtles (representing households or agents) interact with each other and the environment to simulate the process of adaptation to coastal erosion, allowing for a better understanding of how populations can adapt to this natural process. The model environment was represented by a virtual map that simulated the atmospheric conditions and coastal environment of Channel-Port aux Basques. The map comprises a grid of cells, and each cell represents a location on the coast. The environment in the model is dynamic, and it changes over time due to the effects of flooding and coastal erosion. The erosion is simulated through the "*erosion*" variable, which the turtles accumulated over time. As the turtles move across the map, they erode the cells they move through, and different colors represent the cells to indicate the level of erosion.

The turtles move around the map and interact with each other, representing the population and their ability to adapt to coastal erosion. The population is composed of turtles with different colors representing different traits. Yellow turtles represent those with the potential to adapt, and they gradually accumulate erosion over time as they move around the map. Blue turtles represent those without the potential to adapt and remain stable over time.

The model also includes parameters that were adjusted to represent different scenarios. For example, the "relocate-distance" parameter determined the distance that yellow turtles can relocate to blue turtles, simulating the spread of adaptive traits in a population. The "relocate-chance" parameter determined the probability that yellow turtles would relocate to blue turtles, simulating the likelihood of adaptive traits spreading in a population.

Agent-based Modeling for Coastal Erosion

The model first simulated coastal erosion for Channel-Port aux Basques. It modeled the movement of wind, temperature, sea level rise, and storm surge through the coastline of Channel-Port aux Basques. The model includes several breeds of turtles representing different types of particles (storm surge, sea level rise, temperature, and wind speed) and a breed of snow. The turtles move around the atmosphere and interact with each other based on simple rules as seen in the figure below.

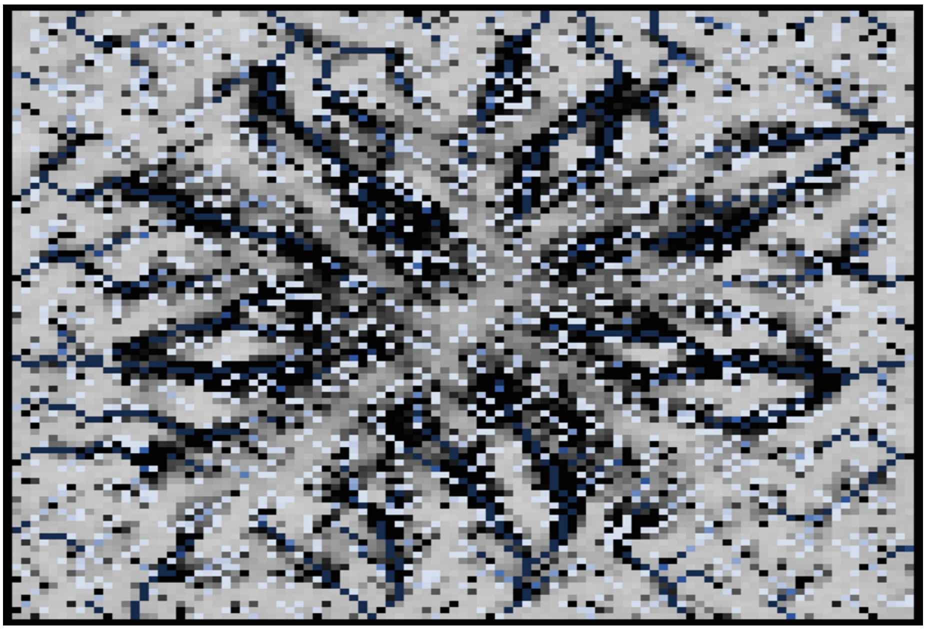

Figure 6: Agent-based model for coastal erosion at Channel-Port aux Basques (Source: Netlogo simulation)

The first rule in the simulation was the *setup* procedure which simulated the town and set the overall temperature. The *setup-world* procedure sets the colors of the particles based on their location. The *go* procedure was the main simulation loop that moved each of the model's subroutines. The *add-snow and remove-snow* procedures created and deleted snow, respectively. The *run-sunshine* procedure created new rays of sunlight and handled sunlight, heat, and temperature at Channel-Port aux Basques. The *run-storm surge* procedure modeled the movement of the storm and changed the overall wind speed based on the balance of incoming and outgoing wind and storm. The *run-sea level* procedure modeled the movement of sea sediments and the rise and fall of sea levels in the simulation.

The model predicts that the shoreline might change over time based on these factors. Based on the location of Channel-Port aux Basques, the model predicts that the area is subject to high wave energy due to its exposure to the North Atlantic Ocean. The model also considers sea level rise, which contributes to coastal erosion by increasing the rate of flooding and erosion, as well as shoreline retreat. The model simulated coastal erosion and flooding based on the severity of storms and sea level rise in the area to evaluate the effectiveness of adaptation measures in reducing the rate of coastal erosion. The model was run for multiple iterations to evaluate the long-term effect of these factors on coastal erosion and flooding. Based on the simulation, the model depicted that if sea-level continues to rise at an average of 3mm, as reported by Catto (2011). The wind speed combines with other particles; households within at least 8 meters from the coast will experience coastal erosion in the first year, and about 12 meters from the coast will experience coastal erosion in the ensuing year. This agrees with what the Municipal Plan mentioned, which is that most of the damages that occur due to coastal erosion and flooding happen within 8 meters above sea level elevation, with some damages occurring up to 12 meters elevation (Provincial and Municipal Affairs, 2022).

Agent-based Modeling for coastal adaption

The adaptation measures that are currently in place in Port aux Basques could also be factored into the model. For example, if the area has seawalls, beach nourishment programs, or other protective measures in place, the model predicted that these measures could mitigate the effects of coastal erosion to some extent. However, the accuracy of the model's predictions would depend on the availability and accuracy of real-time data at Channel-Port aux Basques; hence, the model was considered uncertain and had limitations. It is important to keep in mind that coastal erosion and flooding are complex processes that are influenced by many factors; hence, predicting their adaptation accurately can be challenging.

The model simulated the process of adaptation to coastal erosion by using *turtles* (agents) to represent the households. The agents are randomly placed on the virtual map that represents Channel-Port aux Basques, and some of them are randomly selected to represent those with the potential to adapt, as seen in the model in Figure 7.

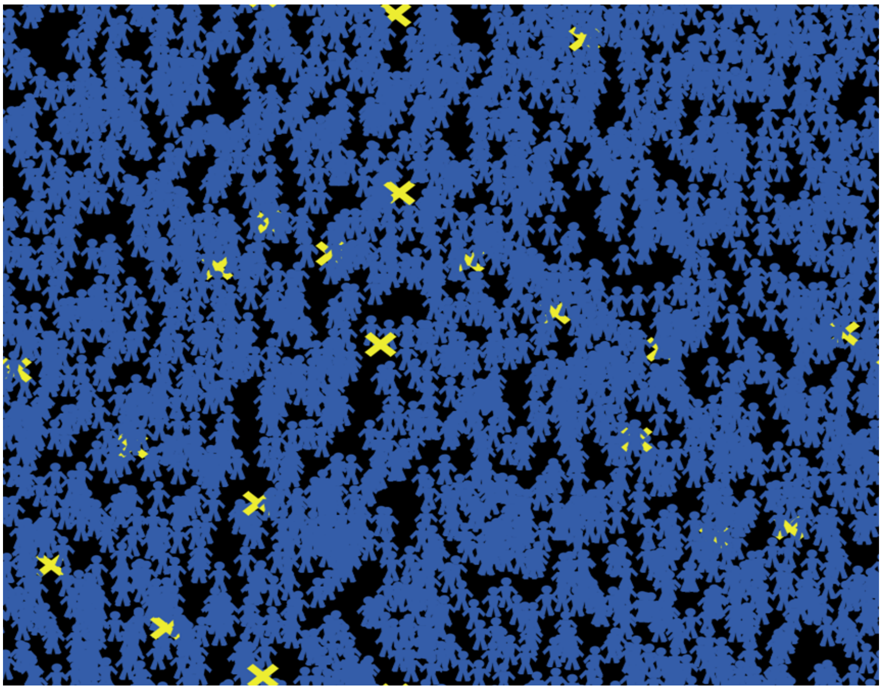

Figure 7: Agent-based model for coastal adaptation - Netlogo Simulation (Source: Netlogo simulation)

These adaptable agents, represented in the model as yellow, experienced "coastal erosion," representing their ability to withstand the effects of coastal erosion. If a yellow turtle's erosion level exceeds a certain threshold, it turns red. It is removed from the population, indicating that it cannot adapt further to the erosion as seen in Figure 8 below. This means that if households are not able to withstand the erosion, they will relocate from the community. If they can withstand the erosion, they stay in the community and invest their resources, such as wealth, to plan and prepare protective measures that can make them adapt to the coastal erosion in the community.

Figure 8: Agent-based modeling for households that cannot adapt to coastal erosion (Source: Netlogo simulation)

The relocation of yellow turtles (agents/households) to nearby blue turtles, as simulated in the model, represents the spread of adaptive traits in a population. The first model was initialized by creating agents or particles to represent the atmospheric conditions and sea level rise at Channel-Port aux Basques by assigning random severity of the flood and coastal erosion to different parts of the coastline. In the second model on adaptation to coastal erosion, each agent assessed the level of erosion near their homes and decided whether or not to invest in coastal erosion adaptation measures based on their income level and the severity of erosion. Those who chose to invest in protective measures allocated a portion of their income towards the chosen adaptation measure. The resources were allocated towards several adaptation measures, including a sea wall, beach nourishment, armor rock, awareness raising, and early warning technology. The model selected the sea wall as the most effective adaptation measure based on the severity of erosion in different parts of the coastline and the effectiveness of different measures.

Turtles or households that do not relocate are initially colored white. They are given seawall protection to simulate the protective effect that seawalls can have on the coastal population of Channel-Port aux Basques. The model incorporates a probability called “waning-seawall,” which simulates the gradual loss of effectiveness of the seawall over time due to coastal processes to reflect whether the seawall can become less effective as the coastline changes and erodes over time. The seawall in the model can offer protection from coastal erosion for some time. The model, therefore, depicted that while the sea wall can protect the community from coastal erosion for some years, it may not be the permanent solution.

This modeling approach has several important implications for understanding the process of adaptation to coastal erosion. First, it suggests that adaptation to coastal erosion is possible. Still, it requires a certain level of resilience and a population with a diversity of traits that can spread over time (Hawick, 2014). Secondly, it highlights that there are limits to adaptation, as some individuals will inevitably fail to adapt to the pressures of coastal erosion and, therefore, choose to relocate. To promote adaptation to coastal erosion, the model suggests that it is necessary to create a resilient population with a diverse set of adaptive traits that can spread over time. This could be achieved by promoting measures that encourage the spread of adaptive traits and help build resilience in communities. Examples of such measures could include creating green spaces and enhancing coastal protection measures.

Probability/uncertainty of the model

To determine the probability of coastal erosion happening at Channel-Port aux Basques, the current distance between residences and the coast and the rate of sea level rise are needed. Given that residents live about 10 meters away from the coast, the distance will be converted to centimeters to be consistent with the sea level rise rate. Hence:

10 meters = 1000 centimeters

The rate of sea level rise is 2.5mm per year, as reported by Batterson and Liverman (2010). So, over a year, the sea level will rise by 0.25 centimeters. Therefore, after x years, the sea level will rise by $0.25x$ centimeters.

To estimate the impact of coastal erosion, the amount of land that is lost or will be lost due to rising sea levels was also considered. Assuming that the slope of the coastline is relatively flat, we can use the formula:

$$\text{Impact} = 0.5 \times (2.5x)^2 \times 3.14 \times 10$$

Where:

0.5 is the constant (for the area of a triangle)

$2.5x$ is the rise in sea level

3.14 is the value of *pi* (π), used for calculating the area of a circle

10 is the length of the coastline that will be affected (i.e., the distance between residences and the coast).

Assuming the coastal erosion might occur if the impact is greater than the land that separates residences from the coast (i.e., 10 meters or 1000 centimeters), the uncertainty equation can be set at:

$$0.5 \times (2.5x)^2 \times 3.14 \times 10 > 1000$$

Simplifying this equation:

$$(2.5x)^2 > 63.66$$
$$2.5x > 7.99$$
$$x > 3.196$$

This means that as the sea level rises at an annual rate of 2.5mm, the land within 10 meters from the sea is likely to be underwater and will likely experience severe flooding and coastal erosion after 3.196 years (or approximately three years and two months). The probability of coastal erosion happening within the next year can also be estimated as follows:

$$P(\text{coastal erosion in next year}) = P(\text{Sea level rise} > 10 \text{ meters})$$
$$= P(2.5x > 1000)$$
$$= P(x > 400)$$

Assuming that the rate of sea level rise is constant and independent over time, a normal distribution can be used to estimate the probability of the sea level rising by more than 400 centimeters (i.e., $x > 400$).

Using the mean of 2.5mm/year and a standard deviation of 0 (since the rate of sea level rise is assumed to be constant), the z-score can be calculated as follows:

$$z = (400 - 0) / (2.5 \, x \, \mathrm{sqrt}(1))$$
$$z = 160$$

Using a z-score table or calculator, the results show that the probability of the sea level rising by more than 400 centimeters (i.e., $x > 400$) is virtually zero (less than 0.0001). Therefore, the probability of coastal erosion happening within the next year is also very low. However, over the longer term, the risk of coastal erosion will increase as sea levels continue to rise. The impact of coastal erosion could, therefore, be severe, with the loss of land within 10 meters of the sea leading to damage or destruction of buildings and infrastructure and increased risk of flooding and other natural disasters. The population of Channel-Port aux Basques could be significantly affected, with potential displacement and economic losses. Hence, the sea wall, as predicted by the model, could be a proactive measure to help the town adapt to the effects of coastal erosion and sea level rise.

Probability Due to Storm

To estimate the probability of coastal erosion due to a storm for three different years, the following equation was used:

P(coastal erosion due to a storm in year i) = P(Wind speed and wave height exceed erosion threshold in year i)

where *i* represents the year of interest.

Historical data was used to calculate the probability of the wind speed, rainfall, and wave height exceeding the erosion threshold. This data was used to estimate the probability of erosion due to a storm based on rainfall, wind, and wave conditions and to estimate the probability of erosion for each of the three years using the equation above. For example, if the statistical model estimates that the probability of erosion due to a storm in a given year is 0.05 (or 5%), the probability of erosion for each of the years is estimated as:

P(coastal erosion due to a storm in year 1) = 0.05
P(coastal erosion due to a storm in year 2) = 0.05
P(coastal erosion due to a storm in year 3) = 0.05

These estimates are based on the assumptions and limitations of the model and the historical data used to develop it. Actual conditions in each year may vary and could lead to erosion probabilities that are different from these estimates.

The equation ***P(coastal erosion due to a storm in year i) = P(Wind speed and wave height exceed erosion threshold in year i)*** is a descriptive equation that relates the probability of coastal erosion to the probability of rainfall, wind speed, and wave height exceeding a certain threshold. One possible statistical equation that can be used to model this situation is a logistic regression model:

$$P = 1 / (1 + \exp(-z))$$

where P is the probability of coastal erosion due to a storm in a given year, and z is a linear combination of predictor variables:

$$z = b0 + b1\textbf{WindSpeed} + \textbf{b2}\textit{\textbf{WaveHeight}} + b3\textbf{StormDuration} + \textbf{b4}\textit{\textbf{StormDirection}} + e$$

In this equation, *WindSpeed*, *WaveHeight*, *StormDuration*, and *StormDirection* are predictor variables that influence the probability of flooding and coastal erosion due to a storm, and ***b0***, ***b1***, ***b2***, ***b3***, and ***b4*** are coefficients that determine the strength and direction of the relationship between each predictor variable and the probability of erosion. The term ***e*** represents random error or variability that is not accounted for by the predictor variables.

To estimate the coefficients of the logistic regression model, historical data on wind speed, wave height, storm duration, storm direction, and erosion events were used to identify patterns and relationships between these variables. It is, however, important to mention that this is just one possible statistical model that can be used to estimate the probability of coastal erosion due to a storm. The specific form of the model may vary depending on the data used, the complexity of the relationship between predictor variables and the response variable, and other factors. Figure 12 below shows the values of the four predictor variables (WindSpeed, WaveHeight, StormDuration, and StormDirection).

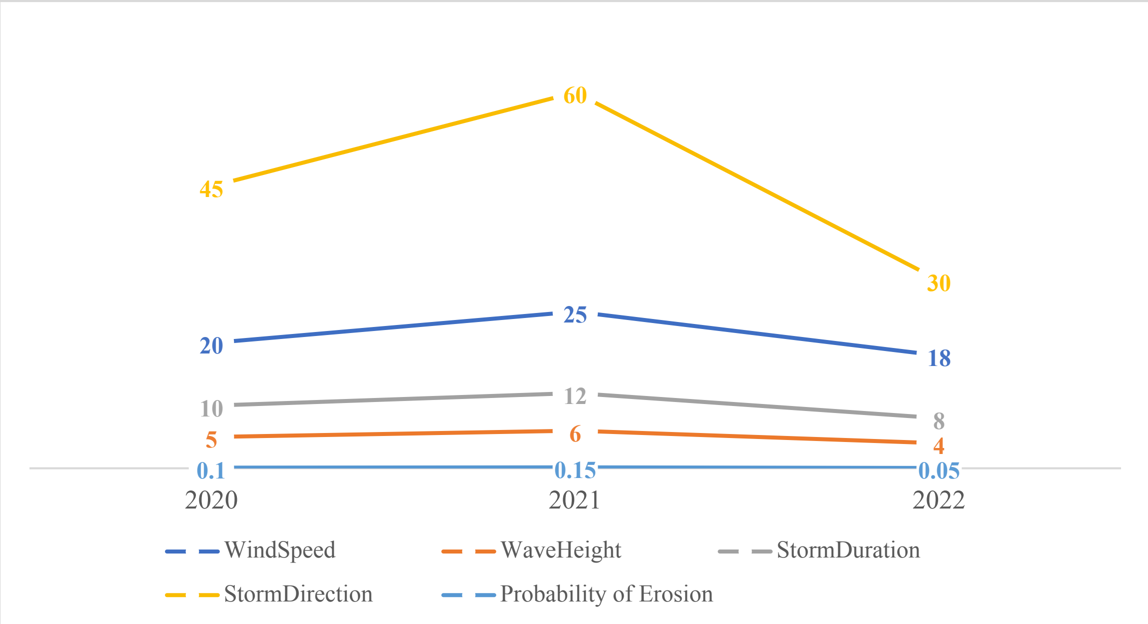

Figure 9: The values of four predictor variables (WindSpeed, WaveHeight, StormDuration, and StormDirection)

Figure 12 shows the values of the four predictor variables (WindSpeed, WaveHeight, StormDuration, and StormDirection) and their resulting probability of coastal erosion due to a storm at Channel-Port aux Basques for three different years (2020, 2021, and 2022). For each year, the figure lists the values of the predictor variables used to calculate the probability of erosion. WindSpeed is measured in units of speed, WaveHeight is measured in units of height, StormDuration is measured in units of time, and StormDirection is measured in units of degrees. The probability of erosion column shows the estimated probability of coastal erosion due to a storm at Channel-Port aux Basques, calculated using the logistic regression equation mentioned earlier.

From the figure, it can be observed that the probability of erosion varies depending on the values of the predictor variables. For example, in 2021, higher values of WindSpeed, WaveHeight, and

StormDuration, as well as a more easterly StormDirection, resulted in a higher probability of erosion. On the contrary, in 2022, lower values of WindSpeed, WaveHeight, and StormDuration, and a more northerly StormDirection, result in a lower probability of erosion. The figure offers a way to understand how different factors can influence the likelihood of flooding and coastal erosion due to a storm at Port aux Basques. It can be used to make predictions about future erosion risk based on the values of the predictor variables.

Conclusion

In conclusion, the study has highlighted the effectiveness of various measures such as education, outreach, monitoring, planning, and regulatory tools in assisting residents to adapt to flooding and erosion challenges. Additionally, the use of armor stones along the coast was highlighted by the model as a strategy to protect the coastline. However, despite these positive outcomes, questions arise regarding the sustainability of these techniques in the event of more severe climate events like stronger hurricanes or accelerated sea-level rise beyond current projections.

The study also utilized agent-based modeling to forecast adaptation to coastal erosion, revealing insights into potential future scenarios. The simulation results indicated that households within a certain proximity to the coast are likely to experience erosion within specific timeframes if sea levels continue to rise. While adaptation to coastal erosion is possible, it necessitates resilience and diverse adaptive traits among the population. The study also highlighted the limits of adaptation, as some individuals may struggle to cope with coastal erosion pressures and may opt to relocate.

Although seawalls were identified as the most effective adaptation measure in the short term, the study's model suggests that they may not provide a permanent solution. Therefore, the study emphasizes the need for a more integrated approach to adaptation, considering long-term sustainability and effectiveness. The research emphasizes the urgency of addressing coastal erosion in Channel-Port aux Basques and advocates for adopting sustainable and context-specific adaptation strategies. It emphasizes the importance of engaging local communities and improving overall resilience to protect infrastructure and residents from erosion impacts amidst changing environmental conditions.

Recommendations

Based on the findings derived from the study above, the research makes the following recommendations: These recommendations are aimed at strengthening Channel-Port aux Basques' resilience to climate change by improving knowledge, building capacity, and implementing effective adaptation measures.

Recommendation for the Municipality

The analysis indicates that the risk of coastal erosion is likely to increase over time as sea levels continue to rise. The impact of coastal erosion could be severe, leading to the loss of land, damage or destruction of buildings and infrastructure, as well as increased risk of flooding and other natural disasters. Therefore, the study recommends that a plan to mitigate the risk of coastal erosion should be developed. One possible solution is to build a sea wall to protect the coastline from erosion and flooding as predicted by the agent-based model.

The study found that flooding and coastal erosion has a significant social, economic, and environmental impact on Channel-Port aux Basques. It is recommended that the municipality should prioritize developing and implementing a comprehensive coastal erosion and flooding management plan that considers the social, economic, and environmental impacts of these events. The plan should focus on developing infrastructure that is resilient to flooding and erosion such as the sea wall predicted in the model and ensuring that there are effective early warning systems, such as sensors, that can provide real-time data to residents and businesses to prepare for potential flooding and coastal erosion to protect lives and properties.

The study further discovered that the town is developing a coastal erosion plan through consultation with the community. It is therefore recommended that the town continues to focus on promoting sustainable land use practices that prioritize the preservation of important coastal ecosystems and allow for managed retreat when necessary. Additionally, it should include measures to raise awareness and educate residents on the importance of not building close to the shoreline.

Furthermore, the study recommends that constant monitoring of sea level rise and weather conditions should be conducted. This will enable proactive measures to be taken to protect the coastline from the impacts of coastal erosion. Also, a more comprehensive and up-to-date vulnerability assessment should be conducted to identify the potential impacts of climate change on the community. This will provide a better understanding of the risks associated with climate change and help to prioritize adaptation measures.

The research recommends a transdisciplinary approach involving all stakeholders to address the complex and interconnected challenges facing the community. The study recommends that the town should collaborate with relevant stakeholders, including researchers, non-governmental organizations, and government agencies, to develop a comprehensive and integrated strategy for managing the impacts of coastal erosion and flooding in the long term. An ongoing stakeholder and community engagement and consultations can lead to the development of more adaptation plans after assessment, monitoring, consultation, and planning are completed. A transdisciplinary approach should be encouraged to ensure that everyone is aware of the issues and working together to find and implement sustainable solutions.

The study proposed building a sea wall as a proactive measure to help the town adapt to and mitigate the effects of coastal erosion and sea level rise. The study recommends that the municipality should incorporate climate change considerations into the municipal plan and decision-making processes to ensure that adaptation measures are considered when making policy and planning decisions. This will require the development of clear guidelines and protocols for decision-making that incorporate climate change projections and vulnerability assessments.

The study further recommends that the town should consider additional adaptation measures, such as nature-based solutions, to complement existing strategies for managing coastal erosion. These could include measures such as restoring wetlands and mangroves to provide natural buffers against storms and sea level rise.

The study also found that there is ongoing consultation with the residents of the community to address the challenge they face from the impact of the flood and coastal erosion. The study recommends that the local communities should be involved in the planning and decision-making processes related to coastal erosion mitigation measures. This will ensure that their concerns are addressed and that the measures are appropriate for the local context.

Finally, the study recommends that there should be monitoring and evaluation of the effectiveness of adaptation measures over time to ensure that they remain relevant and effective in the face of changing climate conditions. This will require the development of robust monitoring and evaluation frameworks that incorporate feedback from stakeholders and the latest scientific data on climate change.

Recommendation for further studies

Based on the results of the study on the impact of coastal erosion, current adaptation strategies, effectiveness of the adaptation strategies, and agent-based modeling, the following research recommendations can be made for future studies:

Conduct a longitudinal study: The current study provided a snapshot of the impact of coastal erosion and adaptation strategies. A longitudinal study could provide a more comprehensive understanding of the impact of coastal erosion over time and the effectiveness of different adaptation strategies.

Explore the effectiveness of nature-based adaptation strategies: The study found that hard engineering strategies such as armor stone were the most commonly used adaptation strategies. Future studies could explore the effectiveness of nature-based adaptation strategies, such as beach nourishment, dune restoration, and wetland restoration.

Investigate the role of stakeholders in adaptation decision-making: The study found that the town council is the primary agent responsible for implementing adaptation strategies. A future study could investigate the role of different stakeholders, including local communities, philanthropic organizations, NGOs, and private sector organizations, in adaptation decision-making.

Develop more sophisticated agent-based models: The study used a relatively simple agent-based model to assess the effectiveness of adaptation strategies. A future study could develop more sophisticated agent-based models that incorporate a wider range of factors, such as economic, social, and environmental variables, to understand the effectiveness of adaptation strategies better.

Limitation

The study did not incorporate primary data from the community due to time constraints. The findings of the current study are, therefore, based on literature analysis. Also, the research was specific to the context of Channel-Port aux Basques and, therefore, may not be generalizable to other coastal communities facing similar challenges. Additionally, the study focused primarily on the impacts and adaptation strategies related to coastal erosion and flooding. It did not consider other potential factors that may be contributing to the issues faced by the community. Finally, while the study provided valuable insights into the current adaptation strategies being used in the community, it did not evaluate the financial resources that will be required to develop and implement effective adaptation techniques.

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Figure 1: Map of Newfoundland showing the location of Channel-Port aux Basques (Source: Climate Central, n.d)

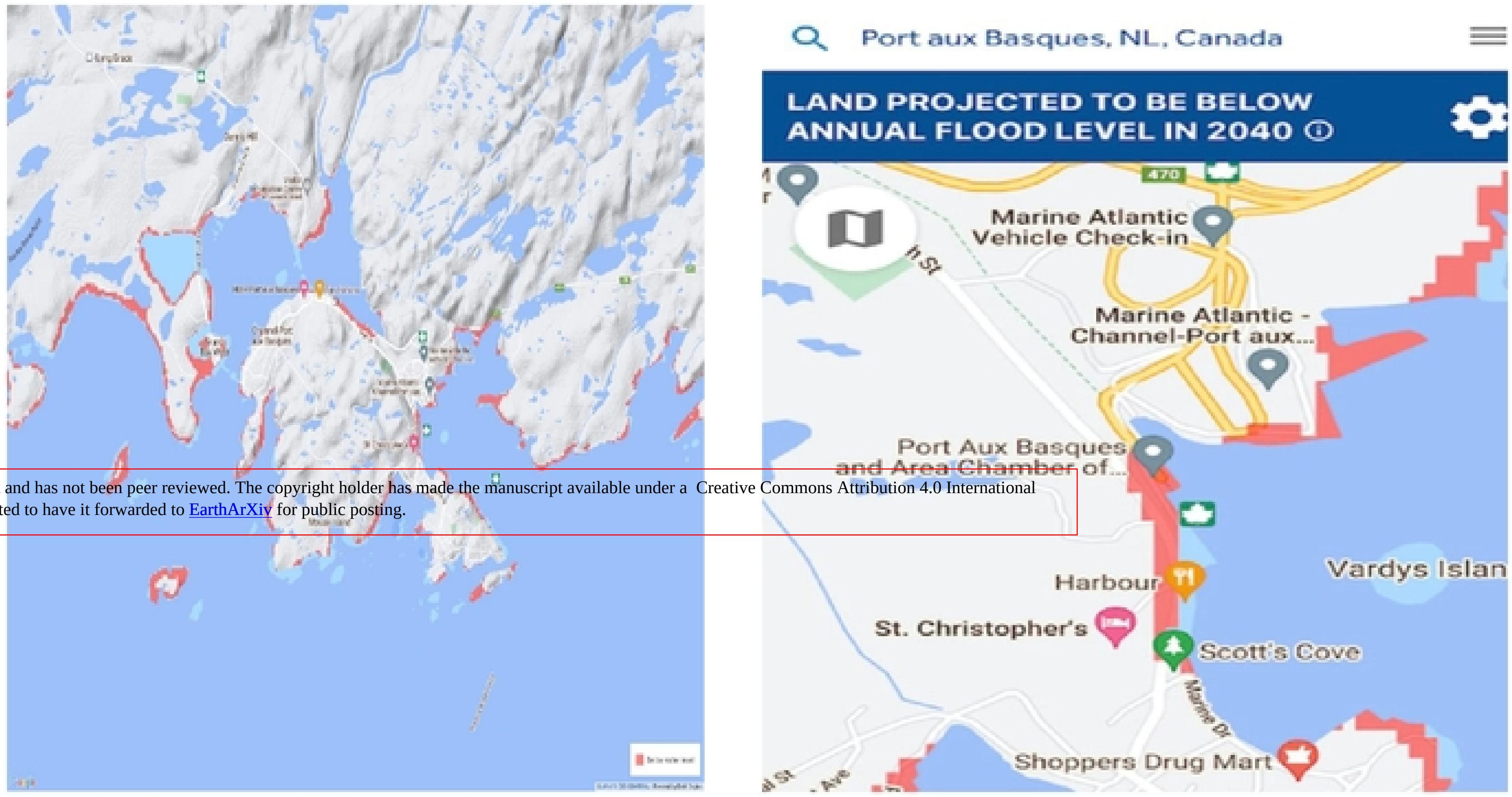

Figure 2: Overview of the case study areas. Left: The case study area is lying below sea level. Right: The case study area prone to flooding and coastal erosion (Source: [Climate Central, n.d]).

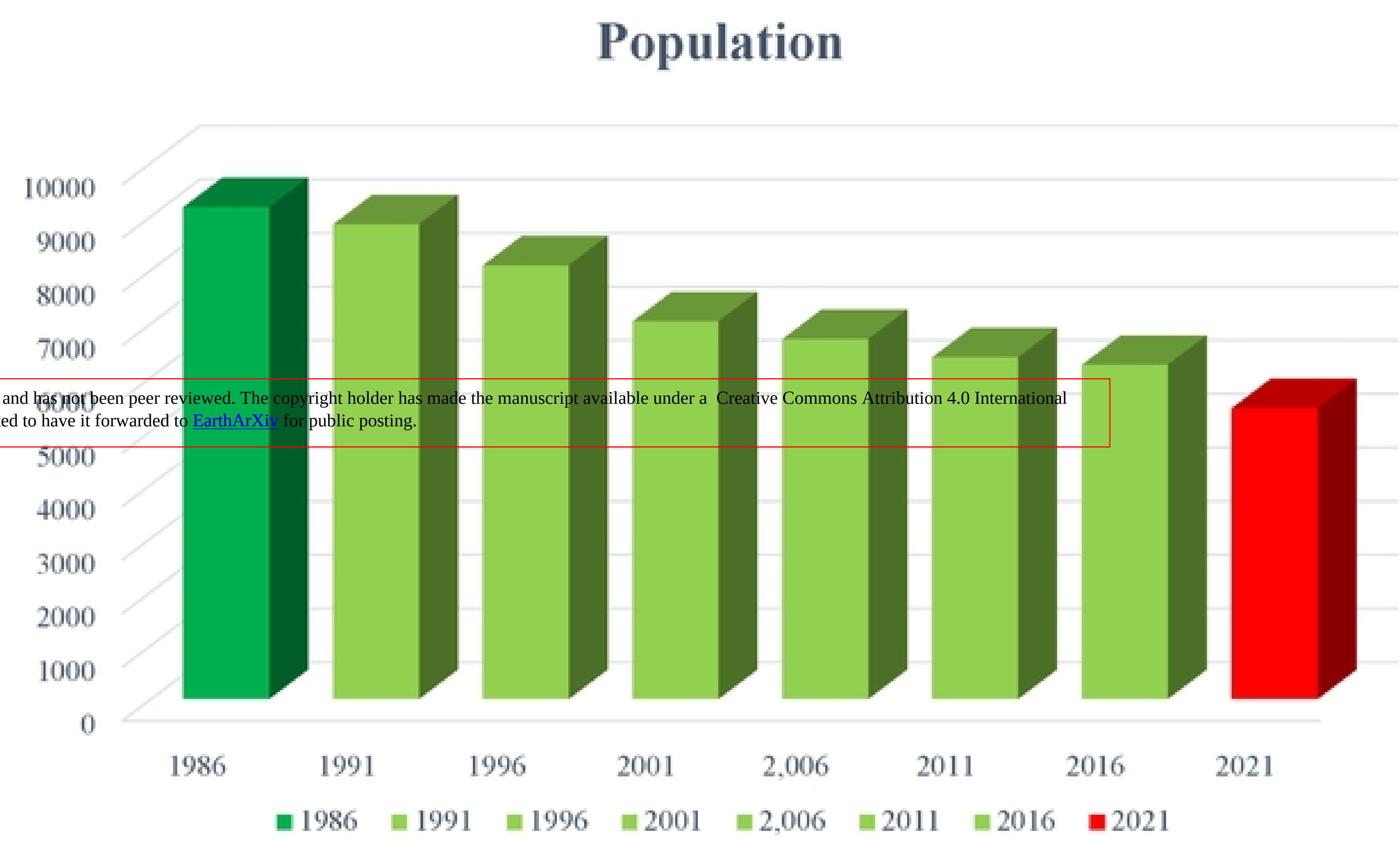

Figure 3: Population of Channel-Port aux Basques from 1986 – 2021 (Data source: Newfoundland and Labrador Statistics Agency, 2021)

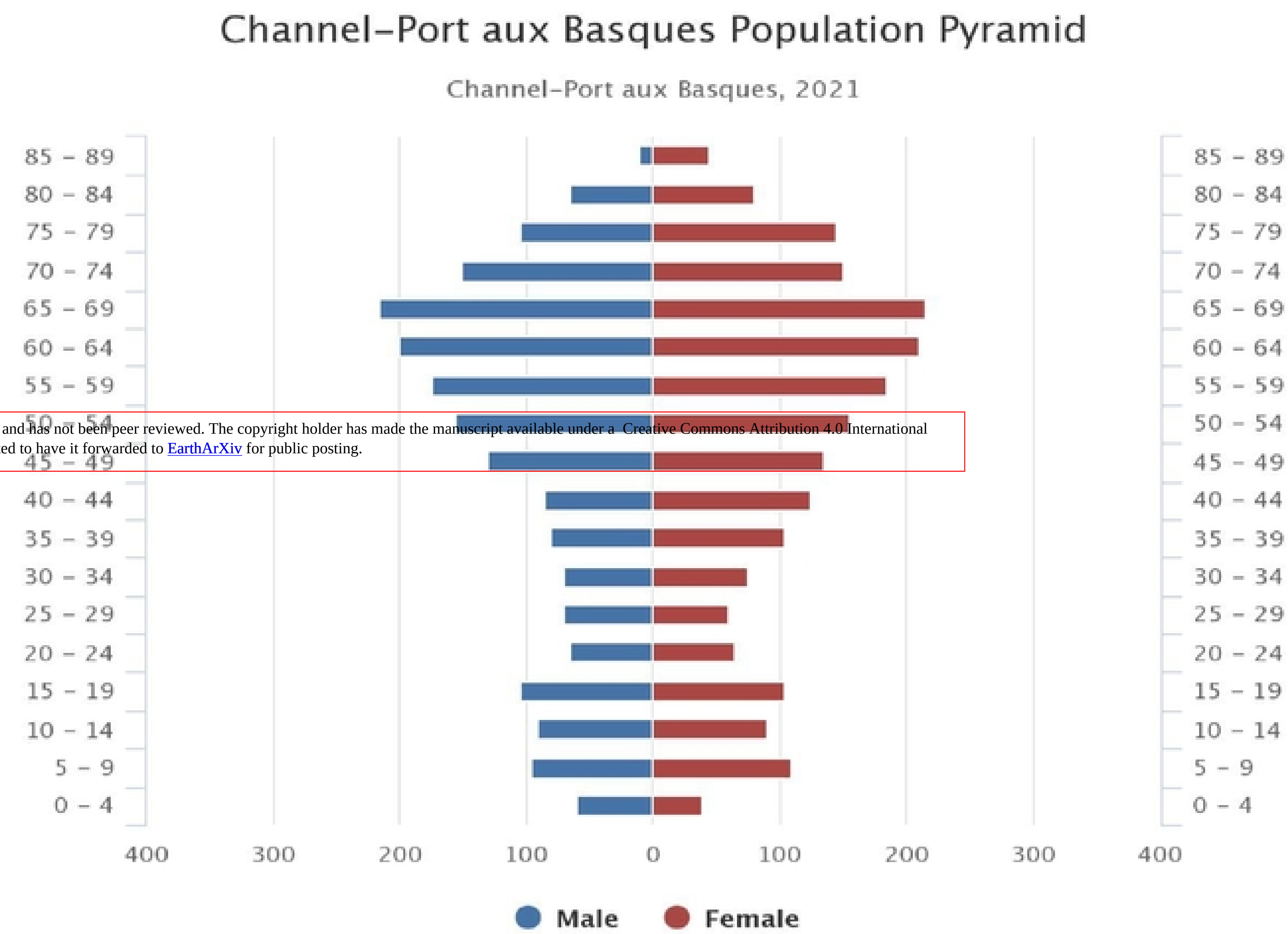

Figure 4: Channel-Port aux Basques 2021 population pyramid (Data source: Newfoundland and Labrador Statistical Agency, 2021)

Housing period of construction (2021 Census)

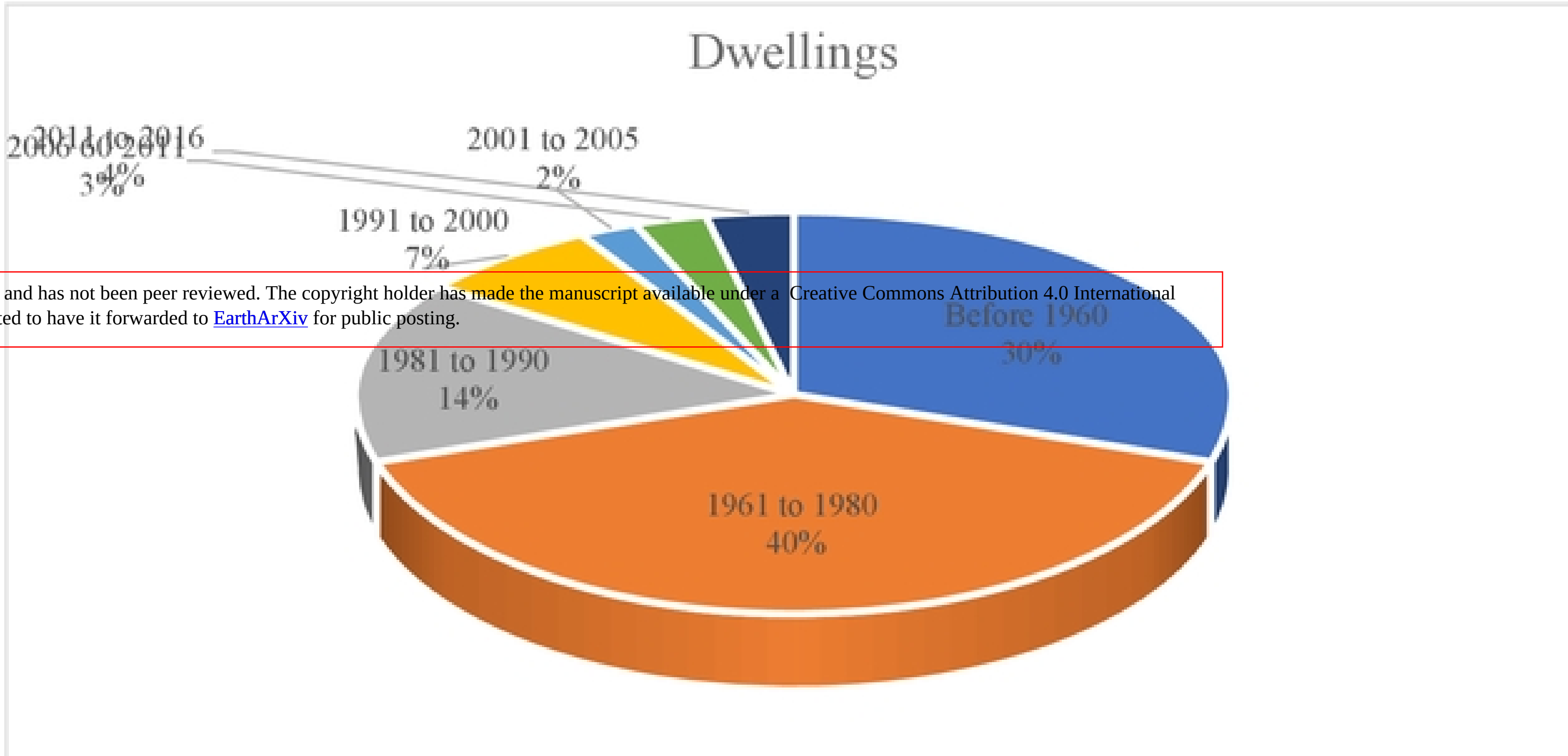

Figure 5: Housing period of construction (Data source: NL Statistics Agency, 2021)

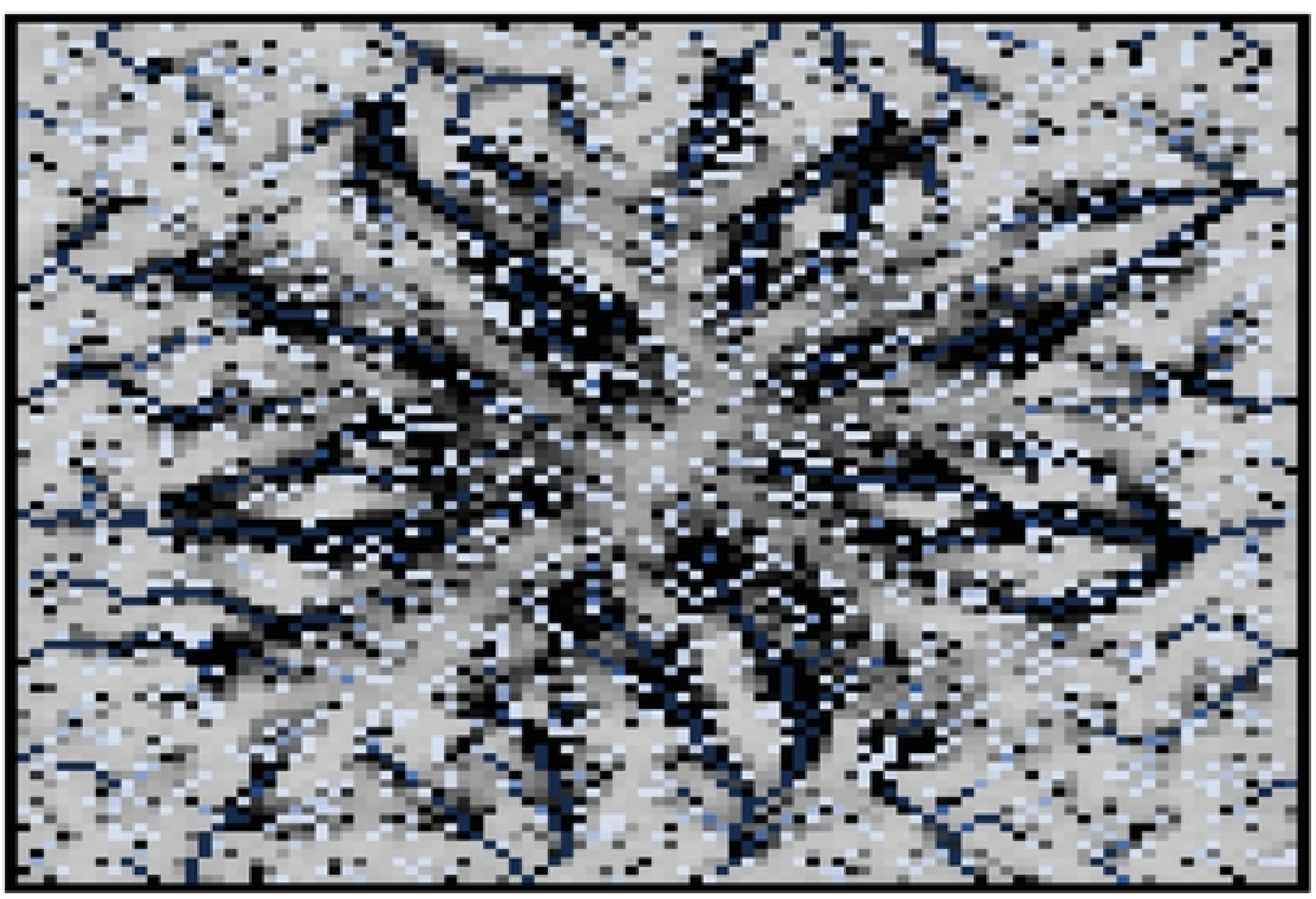

Figure 6: Agent-based model for coastal erosion at Channel-Port aux Basques (Source: Netlogo simulation)

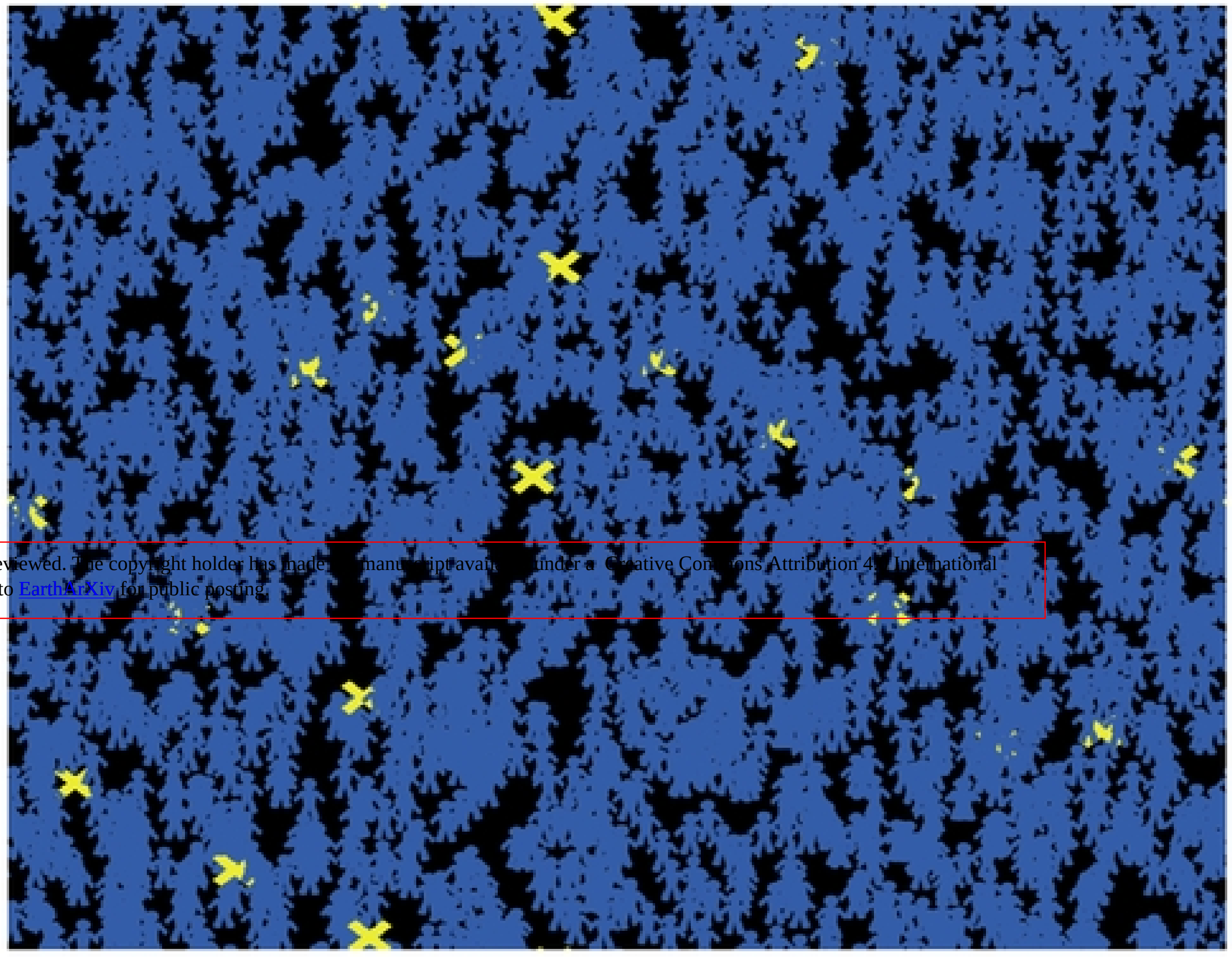

Figure 7: Agent-based model for coastal adaptation - Netlogo Simulation (Source: Netlogo simulation)

Figure 8: Agent-based modeling for households that cannot adapt to coastal erosion (Source: Netlogo simulation)

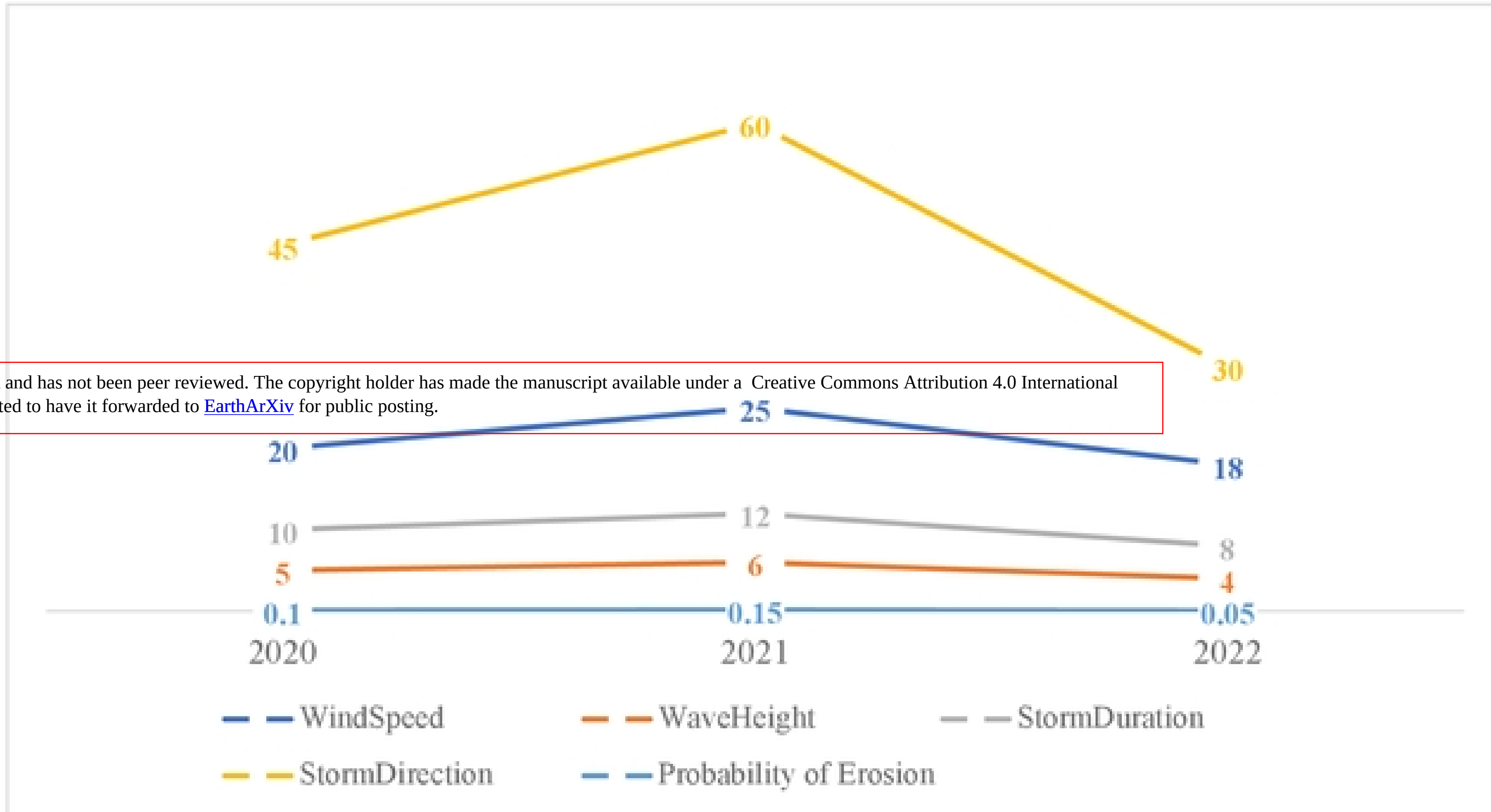

Figure 9: The values of four predictor variables (WindSpeed, WaveHeight, StormDuration, and StormDirection)