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Engineering Evaluation of Freshwater Lake Coastal Sand Dunes: A Study of Sandbanks Provincial Park, Kingston, Canada

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Abstract: This study provides a comprehensive engineering evaluation of the freshwater coastal sand dunes at Sandbanks Provincial Park, located on the southern edge of Prince Edward County, Kingston, Ontario, Canada. Sandbanks is renowned for its extensive and dynamic sand dune system, which plays a crucial role in coastal management by absorbing wave energy, mitigating storm surges, and preventing sand deposition on infrastructure. Shaped by historical glacial activities, wind, and wave action, these dunes are critical for stabilizing the beach environment, controlling wind erosion, and supporting diverse plant and animal communities. This research uniquely combines historical data with recent field studies to offer new insights into the engineering properties, geomorphological processes, and ecological dynamics that govern the formation, stability, and resilience of the dunes. The study addresses contemporary challenges such as climate change, human impact, and erosion, and proposes actionable conservation strategies that balance ecological preservation with practical land management. While focused on a specific section of Ontario's coastal dunes, the findings contribute to a deeper understanding of coastal dune systems more broadly, offering valuable guidance for their long-term sustainability and management across similar environments.

Keywords: Sand Dunes, Ecology, Morphology, Formation Processes, Conservation.

1. Introduction

Sandbanks Provincial Park, located on the southern edge of Prince Edward County, Kingston, Ontario, is home to one of North America's largest and most dynamic freshwater coastal sand dune systems. The park's dunes, shaped by historical glacial processes and ongoing aeolian (wind) and fluvial (water) forces, are a critical component of the region's coastal landscape. As the Laurentide Ice Sheet retreated around 12,000 years ago, it left behind substantial deposits of sand and gravel, which have since been reshaped by wind, water, and vegetation to form a complex system of dunes [1]. The park's dune formations range from embryo dunes on the beach to more stabilized grey dunes, influenced by wind patterns and plant growth [2].

These dunes play a vital ecological role, supporting diverse plant and animal communities

adapted to the harsh coastal environment. They act as natural barriers, reducing wave energy and preventing coastal erosion, thus protecting both infrastructure and the broader landscape [3]. However, the dunes face significant challenges due to the combined effects of climate change, human activity, and natural erosion processes. Rising temperatures, altered precipitation patterns, and the increased frequency of extreme weather events threaten both the stability of the dunes and the biodiversity they support [4]. These factors have prompted a growing need for effective conservation and management strategies.

This paper presents a comprehensive engineering evaluation of the freshwater coastal sand dunes at Sandbanks Provincial Park, with a focus on their geomorphological features, physical properties, and the engineering challenges associated with their preservation. The study aims to assess the dunes' stability by analyzing key characteristics such as grain size distribution, compaction, moisture content, and wind erosion. In doing so, the research seeks to better understand the dunes' vulnerability and propose sustainable strategies for their conservation and management. By integrating ecological and engineering perspectives, this paper provides a holistic analysis of the dunes, emphasizing the critical need for adaptive management practices that account for both natural processes and human impacts.

Ultimately, the goal of this study is to contribute valuable insights into the long-term sustainability of coastal sand dune systems, not only in Sandbanks Provincial Park but also in similar freshwater coastal environments. Through this analysis, we aim to offer practical recommendations that can help mitigate erosion, support biodiversity, and ensure the dunes continue to provide their essential ecological and protective functions.

2. Location of Sandbanks Provincial Park

Sandbanks Provincial Park is in Prince Edward County, Kingston, Ontario, Canada, nestled between the southern shores of Lake Ontario and the rolling landscapes of the county (Fig. 1).

Fig. 1. Location Map of Sandbanks Provincial Park, Prince Edward County, Kingston, Ontario, Canada

The park covers an area of approximately 1,500 hectares and is renowned for its extensive sand dune systems, which are the result of glacial and aeolian processes. Its unique position along the Great Lakes shoreline endows it with a distinctive environment characterized by sandy beaches, shallow turquoise waters, and a diverse range of flora and fauna adapted to the coastal and dune habitats [5].

3. Geological and Environmental Setting

Sandbanks Provincial Park is situated on the southern shores of Lake Ontario, where the sand dunes form a distinctive coastal landform shaped over thousands of years by both glacial and post-glacial processes. The region's underlying geology is primarily composed of sandstone, shale, and limestone formations, with the sandbanks themselves consisting of fine to medium-grained quartz sand [6]. These dunes are dynamic systems, continuously evolving through a combination of factors including wind action, wave erosion, sediment transport, and vegetation growth.

The climate in the region is characterized by cold winters and warm summers, with significant seasonal variations in wind speed and direction that play a crucial role in the formation and movement of the dunes. During the fall and winter months, strong winds are the primary agents of sediment transport, reshaping the dunes, while the summer months experience less intense wind activity but higher levels of precipitation, which contribute to dune stabilization through plant growth and moisture retention [7].

Coastal dunes are integral to both environmental sustainability and coastal protection, offering vital services that enhance ecosystem stability and support infrastructure. These dunes function as natural barriers, reducing wave energy, mitigating storm surges, and preventing erosion, which is crucial for protecting coastal roads, buildings, and other infrastructure [8]. Additionally, the dunes provide critical habitats for a variety of plant and animal species adapted to the harsh coastal environment. Their ability to absorb and filter water also plays a role in maintaining water quality by preventing the runoff of sediments into nearby water bodies.

The environmental significance of these dunes extends beyond their protective functions. They support a diverse array of flora and fauna that depend on the unique habitats formed by the dunes and adjacent coastal ecosystems. The complex interaction of sand, wind, vegetation, and climate ensures the dunes' role in maintaining biodiversity and providing a buffer against the impacts of climate change, including rising sea levels and increased frequency of extreme weather events [4].

3.1. Engineering Significance of Coastal Dunes

Coastal dunes are increasingly recognized as integral components of engineered coastal defense systems, serving to enhance the resilience of coastal areas against climate change and extreme weather events. Their natural protective functions can be reinforced through targeted restoration and engineering practices.

Sand dunes are vital for safeguarding coastal infrastructure by acting as natural barriers that prevent the deposition of beach sands on roads and other structures. They absorb wave energy and mitigate storm surges, reducing impact on inland areas. By stabilizing the beach environment and controlling wind erosion, dunes minimize the transport of sand over roads and buildings. Additionally, dunes support diverse ecosystems and reduce the need for costly artificial barriers, making them a key component of effective coastal management and maintenance.

3.1.1. Natural Protection

Coastal dunes play a crucial role in protecting inland areas from the impacts of storm surges, high waves, and erosion. They function as natural barriers that absorb and dissipate wave energy, significantly reducing the risk of coastal flooding and shoreline erosion [4]. In addition, dunes act as buffer zones that mitigate the effects of strong winds and high waves, stabilizing the coastline and

preventing damage to both natural ecosystems and human infrastructure [9].

3.1.2. Water Filtration and Groundwater Recharge

An essential ecological service provided by coastal dunes is groundwater recharge. As rainwater percolates through the sandy substrate, it undergoes natural filtration, improving water quality and replenishing aquifers. This process is vital for maintaining freshwater supplies in coastal regions [7]. The ability of dunes to filter water and act as a buffer against saltwater intrusion makes them crucial for sustaining both terrestrial and aquatic ecosystems.

3.1.3. Coastal Defense Structures

Engineers often incorporate natural coastal dunes into coastal defense strategies to amplify their protective capacity. Dune restoration projects aim to reinforce these systems, improving their ability to control flood risks and prevent erosion [10]. In some cases, artificial dunes or engineered barriers are created to supplement or replicate the protective functions of natural dunes. These artificial structures are designed to mimic the sand transport and stabilizing functions of natural dunes, ensuring continued coastal protection in areas where natural dunes have been compromised [11].

3.1.4. Erosion Control and Stabilization Techniques

Effective erosion control is vital for preserving the integrity of coastal dunes. Engineers use various techniques to stabilize dunes and prevent erosion, including vegetation planting, installation of geotextiles, and the use of sand fences. These measures are essential for maintaining the dunes' structural stability and enhancing their protective functions [11]. The strategic stabilization of dunes ensures that they continue to serve as natural buffers against coastal hazards.

3.1.5. Infrastructure Planning

When developing coastal infrastructure, it is crucial to account for the dynamic nature of dunes. Engineers and urban planners must consider the potential impacts of development on dune systems to ensure the protection of roads, buildings, and other infrastructure. Sustainable land-use planning practices can help minimize human impacts on dunes and contribute to their long-term preservation [12].

3.2. Ecological Significance

The sand dunes at Sandbanks Provincial Park provide crucial ecological services that support a variety of plant and animal species, while also contributing to broader regional ecosystem health. The dunes offer unique habitats for both terrestrial and marine species, helping to sustain biodiversity in the region.

3.2.1. Habitat and Biodiversity

Coastal dunes are home to unique ecosystems that support a variety of specialized plant and animal species adapted to the harsh coastal conditions. These ecosystems are crucial for the survival of rare and endemic species, and the dunes provide vital nesting and feeding grounds for birds, including endangered species. The dunes also serve as important habitats for small mammals, insects, and reptiles [13]. This biodiversity is not only critical for maintaining ecosystem health but also contributes to the overall ecological balance of the region.

3.2.2. Carbon Sequestration

Vegetated coastal dunes also play an important role in mitigating climate change through carbon sequestration. By capturing and storing carbon in both plant biomass and soil, these dunes contribute to reducing greenhouse gas concentrations in the atmosphere [14]. The preservation and restoration of dune vegetation are therefore integral to climate change mitigation strategies in coastal environments.

3.2.3. Flora and Vegetation

Coastal dunes are home to a variety of specialized plant species that have adapted to the harsh environmental conditions of shifting sands and saline winds. Key plant species include **Marram grass** (*Ammophila breviligulata*), which plays a pivotal role in stabilizing the dunes due to its deep root system and ability to trap sand. Other

pioneer species, such as **beach pea** (*Lathyrus japonicus*), establish themselves in the early stages of dune formation, gradually creating conditions that support more complex plant communities as the dunes mature [6].

3.2.4. Fauna and Wildlife

The dunes also provide critical habitat for a variety of wildlife species. Migratory birds, such as sandpipers and plovers, rely on the beaches for nesting and as a stopover during migration [3]. The surrounding woodlands support mammals like **white-tailed deer** (*Odocoileus virginianus*) and **red foxes** (*Vulpes vulpes*), while reptiles and amphibians such as the **eastern garter snake** (*Thamnophis sirtalis*) and **painted turtle** (*Chrysemys picta*) thrive in the wetland areas adjacent to the dunes [10]. The diverse fauna supported by these dunes highlights their importance as a refuge for both resident and migratory species.

4. Morphology and Types of Coastal Sand Dunes

Coastal sand dunes are characterized by their complex morphology, which includes primary dunes, secondary dunes, and interdunal areas (depressions between dunes). In Sandbanks Provincial Park, the sand dune system consists of a combination of well-developed, steep foredunes at the shoreline, with flatter, more vegetated secondary dunes further inland. The dunes vary in height from 10 meters to over 20 meters in some areas [6] (Fig. 2).

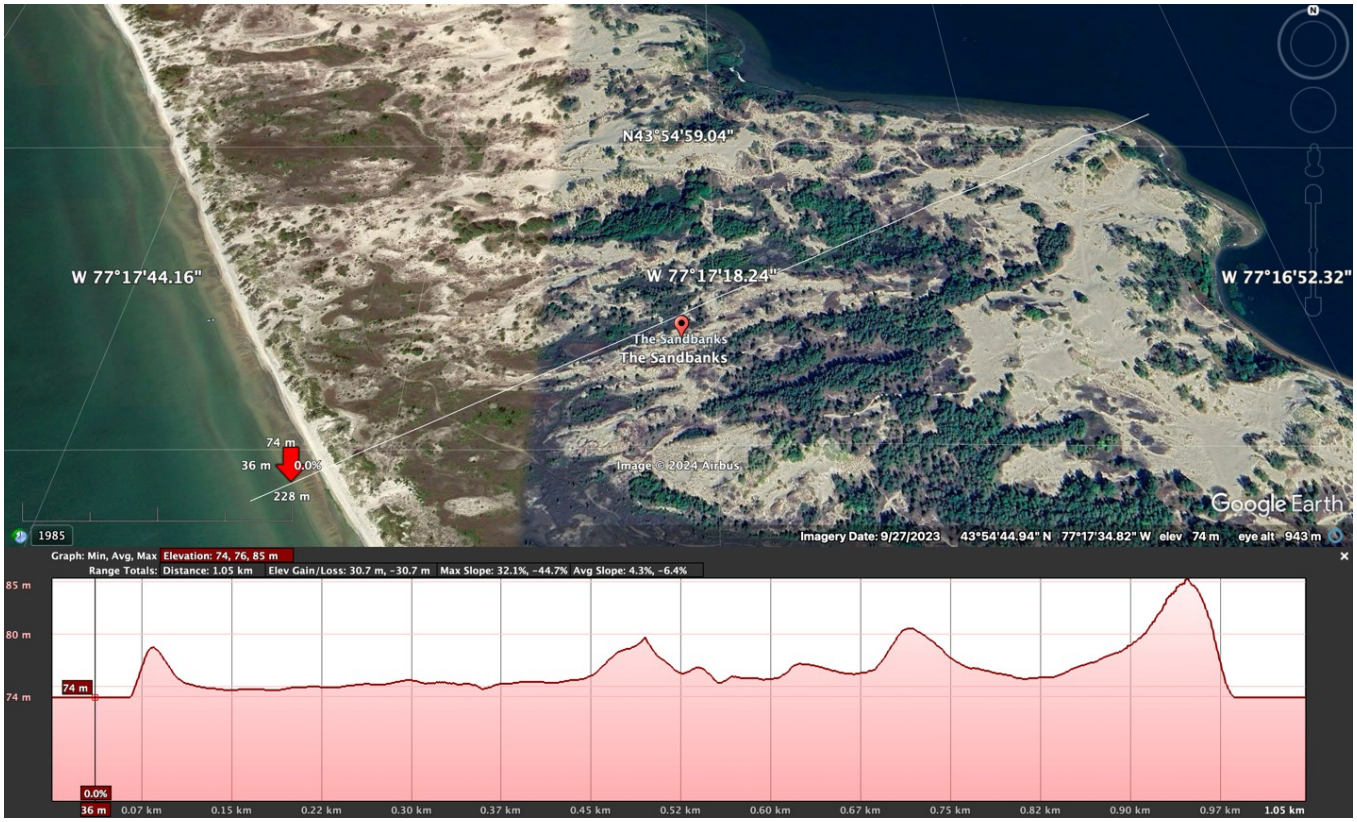

Fig. 2. Cross-Section Profile of Sandbanks showing variations of Sand dunes' Elevations

The primary foredunes, located closest to the lake, are subject to frequent disturbance from wind and wave action, leading to constant reshaping of their structure. In contrast, secondary dunes further inland are more stable due to the establishment of vegetation, which helps bind the sand and prevent erosion. The interplay between wind, vegetation, and moisture content is crucial in determining the stability and resilience of the dunes.

Field surveys conducted in the park have shown that the dunes are largely composed of fine to medium-grained sand, with a consistent grain size distribution that allows for the formation of ripples and dune ridges under the influence of prevailing wind patterns. The sandbanks are also influenced by wave action, with periodic high-water

levels and storm surges eroding the lower portions of the dunes and contributing to the movement of sediment along the coast [7].

The Table 1 provides an overview of the various types of sand dunes, highlighting their unique characteristics, formation environments, and ecological roles. Each dune type is categorized based on its formation process, stability, vegetation, and the conditions in which it typically occurs. This classification helps in understanding the diversity and dynamics of sand dune systems in coastal and inland environments. The references cited offer additional insights into the specific attributes and significance of each dune type.

The predominant types of fresh water coastal dunes in the Sandbanks Provincial Park, Kingston, Ontario lake area are transverse dunes, including foredunes, and parabolic dunes like in other parts of the world (Fig. 3).

Table 1. Classification and Characteristics of Sand Dune Types

Dune Type	Description	Characteristics	References
Embryo Dunes	Initial, small dunes forming directly on the beach, often around obstacles.	Sparse vegetation, loose sand	[15]
Foredunes	Located closer to the shoreline, stabilized by vegetation like Marram grass.	More stabilized, helps build and maintain dunes	[16]
Yellow Dunes	Progress inland, gaining a yellowish hue from accumulated organic material.	Supports a diverse plant community	[6]
Grey Dunes	Older and more stabilized, featuring dense vegetation.	Includes grasses, wildflowers, shrubs; ecologically diverse	[17]
Parabolic Dunes	U-shaped dunes with tips pointing downwind, migrate inland over time.	Formed in areas with consistent wind patterns and abundant sand	[18]
Transverse Dunes	Long, wavy ridges aligned perpendicular to the wind direction.	Formed in environments with plentiful sand and strong winds	[19]

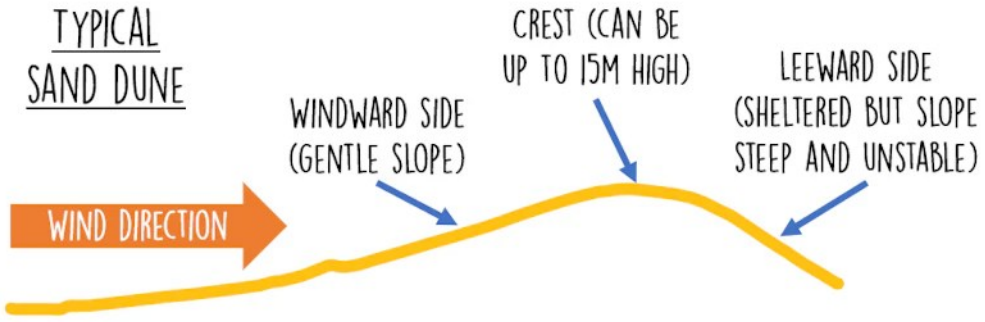

Fig. 3. Morphology of Sand dune

(Adopted from https://www.tutor2u.net/geography/reference/landforms-of-deposition-sand-dunes-aqa-gcse-geography-coastal-landforms-7).

5. Engineering Properties of Sand Dunes: Grain Size Distribution

The grain size distribution of sands in coastal dunes plays a critical role in the mechanical properties, stability, and behavior of dune systems. In freshwater lake environments, such as those along the coasts of Ontario's Great Lakes, the grain size of sand dunes varies depending on factors such as the local sediment source, wave and wind action, and the distance over which the material

has been transported before deposition. Understanding the grain size characteristics of these dunes is essential for both ecological management and geotechnical assessments of coastal stability.

Coastal dunes along Ontario's lakes, particularly around the Great Lakes, generally consist of fine to medium sands, though variations are observed based on local conditions. For example, the dunes at Sandbanks Provincial Park, located along the south shore of Lake Ontario near Belleville and Kingston, are typically composed of well-sorted sands, ranging from 0.1 mm to 0.5 mm in diameter, with a significant portion falling between 0.2 mm and 0.3 mm. These grain sizes are characteristic of medium to fine sand and reflect the prolonged transportation of sediments by wind and wave action, resulting in well-rounded grains that have undergone significant sorting [20, 21].

The sand dunes in the Sandbanks, Belleville, and Kingston areas exhibit a bimodal distribution of grain sizes. Coarser grains tend to accumulate on the windward side of dunes, where wind speeds are higher, while finer grains are found on the leeward side, where wind velocities are lower. This layering pattern is a result of saltation and suspension processes, where heavier grains settle near the dune base, and finer particles are carried further by wind, only to be deposited in sheltered areas [20, 21].

Geotechnical studies indicate that grain sizes vary based on proximity to the shoreline, wind conditions, and seasonal patterns of wave and wind action. Near the shoreline, where wave influence is stronger, the sand is coarser, as larger grains are transported and deposited by waves. Further inland, where wind becomes the dominant force, the sand grains are finer [22]. This results in a gradation from coarser sands near the shoreline to finer sands further inland, with finer grains often accumulating on the sheltered leeward side of dunes.

The geotechnical properties of these sands, such as compaction, shear strength, and cohesion, are influenced by their grain size distribution. Finer sands, typically found inland, tend to have lower shear strength and are more prone to erosion, particularly in areas with little vegetation or where human disturbance occurs [22]. Conversely, coarser sands near the base of dunes are more stable due to their higher frictional resistance, making them less susceptible to wind erosion. In areas with sparse vegetation, finer sand particles are more easily mobilized by wind, leading to dune degradation [23]. Vegetation, such as grasses and shrubs, plays a critical role in stabilizing dunes by reducing wind speed at the surface and promoting the deposition of sand, which helps protect dunes from erosion, particularly in areas dominated by fine-grained sands.

In conclusion, the grain size distribution of sand dunes along the Ontario Great Lakes, specifically in regions like Sandbanks, Belleville, and Kingston, is predominantly medium to fine, with a significant portion falling within the 0.2 mm to 0.3 mm range. The dunes exhibit a bimodal grain size distribution, with coarser sands near the base or on the windward side, and finer sands accumulating on the leeward sides. These grain size characteristics directly influence the dunes' geotechnical properties, including their stability, erosion potential, and shear strength. Understanding these properties is crucial for effective coastal management, especially in the context of climate change and human activity, which can alter sediment transport processes and impact the long-term stability of these coastal ecosystems.

6. Suitability of Freshwater Lake Sand Dunes as Construction Material

Sea dunes, which form along coastlines, are predominantly composed of well-rounded, quartz sand that has been extensively sorted by marine forces such as ocean waves and currents. This results in sand grains that are finer and more uniform in size [24]. The structure of sea dunes is typically complex, featuring well-defined layers

such as embryonic dunes, foredunes, and back dunes, shaped by the high-energy environment of the sea, including tidal processes and salt spray [20]. Although the continuous action of marine forces contributes to a high degree of sorting and rounding of the sand grains, making sea dune material seemingly suitable for construction, the presence of salt in sea dune sand poses significant challenges. The salt content can lead to issues such as corrosion of reinforcement bars in concrete and can compromise the durability of construction materials [19].

In contrast, freshwater lake dunes consist of quartz sand that is generally more angular and less well-sorted compared to marine sand [25] (Fig. 4). This sand often includes a variety of other minerals influenced by local geological conditions and erosion processes. Freshwater lake dunes have a simpler structure, with less pronounced layering and lower overall heights due to less dynamic wind patterns and the absence of tidal influences [26]. Despite its less uniform texture, freshwater dune sand is typically free from salt, making it more suitable for construction purposes, particularly for high-grade applications where the absence of salt is crucial [27]. However, the variable quality and environmental impacts associated with sand extraction from freshwater dunes must also be considered [28]. Consequently, while freshwater dune sand may be preferred for construction due to its lack of salinity, its suitability can still be influenced by other factors such as grain size and mineral composition.

In comparing sand dune materials from freshwater lake dunes and sea dunes, important considerations arise regarding their suitability for construction. Sea dunes, characterized by well-rounded, uniformly sized quartz sand shaped by marine forces, might initially seem ideal for construction applications due to their consistent grain size and shape [24, 29]. However, the presence of salt in sea dune sand can be a significant drawback, as salt can adversely affect concrete quality by causing corrosion of reinforcement bars and weakening the overall structure [30]. In contrast, freshwater lake dunes consist of more angular and less well-sorted sand, influenced by local geological conditions and less dynamic environments. Although this sand is generally less uniform, it lacks the problematic salinity associated with sea dune sand [23, 26]. Therefore, freshwater dune sand may be more suitable for construction purposes, particularly in high-grade applications, due to its absence of salt and potentially better physical properties for such uses [27]. Nonetheless, the extraction of sand from freshwater dunes poses significant environmental concerns, such as disruption of local ecosystems and hydrology, which must be carefully managed to mitigate adverse impacts [28].

Fig. 4. lake shore (Littoral Zone) Sand, Sandbanks Provincial Park

7. Formation of Freshwater Lake Beaches and Sand Dune at Sandbanks

At Sandbanks, the dunes exhibit different stages of development. Embryo dunes evolve into more complex forms such as foredunes, yellow dunes, and grey dunes as the system matures. Other dune types, such as parabolic and transverse dunes, form under specific conditions of wind patterns and sand availability (Table 1). Each type of dune represents a different phase in the natural progression of dune formation [2].

7.1. Freshwater Lake Dunes

The sand dunes at Sandbanks Provincial Park are classified as freshwater lake dunes due to their location along the shores of Lake Ontario, a large freshwater lake (Fig. 5 & 6). This type of dune system is distinct from coastal dune systems found along saltwater beaches. Freshwater lake dunes typically experience lower salinity levels and different ecological dynamics compared to their saltwater counterparts. The vegetation in these dune systems is adapted to less saline conditions and often includes species that are not found in saltwater environments [31, 2]. Additionally, freshwater lake dunes are influenced by lake-level fluctuations, which can affect sediment deposition and dune stability differently than coastal dunes exposed to tidal action [18] and in case of lake dune by wave actions.

7.2. Formation Processes

The sand dunes at Sandbanks Provincial Park, located along the freshwater shores of Lake Ontario, are a striking example of depositional landforms shaped by both glacial history and ongoing environmental processes. The origins of these dunes trace back to the retreat of the Laurentide Ice Sheet, which left behind extensive deposits of sand and gravel (Fig. 7). This glacial legacy was further influenced by the fluctuating levels of glacial Lake Iroquois, the precursor to Lake Ontario, which contributed additional sediment to the region.

The formation of the coastal sand dunes at Sandbanks Provincial Park involves a blend of various environmental factors and processes. Primarily, these dunes form through the accumulation of sand at the back of sandy beaches (Fig. 7 & 8). Key conditions for dune development include a wide, flat beach, an abundant supply of sand, onshore winds, and natural obstacles such as tree roots or driftwood that aid in trapping and stabilizing the sand.

Fig. 5. Longitudinal profile of Sand Dunes at Sandbanks

Fig. 6. Cross section of Coastal Sand Dunes, Sandbanks Provincial Park

Fig. 7. Freshwater Lake beaches and Sand Dunes, Sandbanks Provincial Park

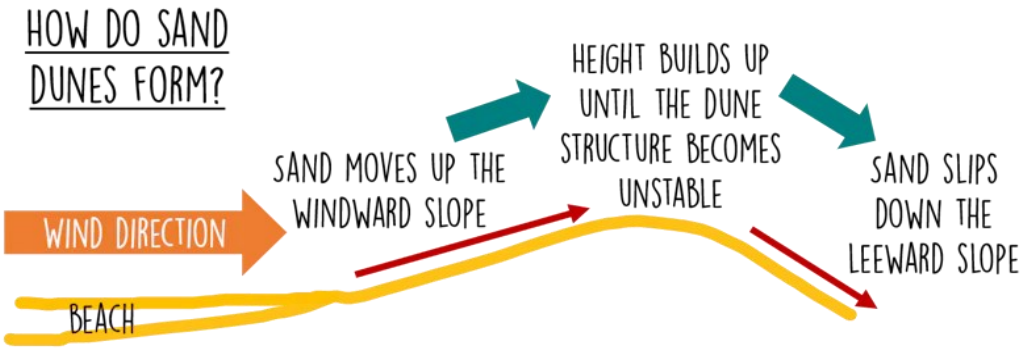

Fig. 8. Formation of Sand dunes

(Adopted from https://www.tutor2u.net/geography/reference/landforms-of-deposition-sand-dunes-aqa-gcse-geography-coastal-landforms-7).

Unlike coastal environments influenced by marine tides, the freshwater dunes of Lake Ontario do not experience significant tidal ranges. Instead, the dunes are shaped primarily by onshore winds, which transport sand towards the back of the beach (Fig. 8). These winds, combined with natural obstacles, initiate the deposition of sand and foster dune growth.

7.3. Mechanisms of Sand Movement

The process of dune formation involves several mechanisms of sand movement. Saltation, where sand grains bounce along the surface, constitutes approximately 95% of sediment transport. Suspension (4%) and creep (1%) also contribute to sand movement. As wind-blown sand encounters obstacles, the heaviest grains settle and form small ridges. Over time, these ridges grow as lighter grains accumulate on the leeward side, forming a crest. The crest's steepness can lead to instability, causing it to collapse and redistribute sand (Fig. 6). This cycle of accumulation, collapse, and migration results in the inland movement of dunes. At Sandbanks Provincial Park, the dunes typically reach heights of around 20 meters, influenced by local wind patterns and sediment availability (Fig. 2).

Sand dune succession at Sandbanks Provincial Park illustrates changes in dune morphology and vegetation as one moves inland. The dunes closest to the lake, known as embryo dunes, are relatively low, while those further inland can reach heights of approximately 20 meters. Vegetation, such as marram grass, plays a crucial role in stabilizing and binding the sand, contributing to the dunes' growth and stability. As dunes mature, they become more vegetated and less sandy, shifting from yellow to grayish hues.

Between parallel lines of dunes, slacks or troughs form where sediment is removed from the leeward side of one dune and the windward side of the next. These slacks may occasionally reach the water table, leading to the formation of small ponds. Additionally, blowouts—large depressions created by the removal of sand due to strong winds—can occur when the protective vegetation layer is disturbed. These dynamic processes highlight the ongoing changes within the dune system and underscore the importance of ongoing management efforts to preserve and protect these unique coastal features.

7.3.1. Wave Action and Longshore Drift

Wave action is pivotal in shaping freshwater lake beaches and dunes. As waves continuously hit the shoreline, they erode and transport sand, creating and modifying beach profiles. Longshore drift, where waves move sand parallel to the shore, contributes to the development of coastal features like spits and sandbars. This movement of sand along the lake's edge is crucial for the formation and evolution of dunes [32].

7.3.2. Wind and Aeolian Transport (Wind Action)

The primary force driving dune formation is wind, which transports and deposits sand along the

shore. Wind plays a major role in the formation and movement of sand dunes. It transports sand from the beach inland, leading to the development of various types of dunes. The characteristics of these dunes are influenced by wind strength and direction, as well as the presence of vegetation, which helps stabilize the dunes and affects their development [31].

According to Bagnold's Law of aeolian transport, the rate of sediment transport (Q) is proportional to the cube of wind velocity (U) and the sediment concentration (S), with an empirical constant (C) that is dependent on the sediment type [1]. This means that higher wind velocities, which are common in coastal environments, can lead to greater sediment transport and deposition. The interaction of wind with the shoreline can transport sand in a process known as **saltation**, where sand grains are lifted, carried short distances, and then fall back to the surface, further contributing to the growth of dunes [32].

Freshwater lake coastal dunes typically form in areas with a consistent onshore or offshore wind direction, which leads to the accumulation of sand in the lee of natural or artificial obstacles, such as vegetation, rocks, or other dunes. The dune-building process begins when wind removes loose sand from the shore and deposits it as ridges or mounds upwind, gradually forming a dune structure [33].

7.3.3. Sediment Supply and Shoreline Dynamics

In addition to wind, the availability of sediment plays a critical role in the formation of dunes. The sediment supply (S) is primarily derived from the erosion of nearby banks, fluvial inputs, and longshore transport. The interaction between wave action and sediment deposition on the shore also influences the extent of dune formation. During periods of high-water levels, wave action can erode the shoreline, redistributing sand and creating conditions conducive to dune formation [22]. In freshwater lakes, where wave energy is generally lower than in marine environments, the interaction between waves and the shoreline is often less intense, but still sufficient to contribute to sediment mobilization and accumulation along the shore.

A simplified model for estimating dune height, based on sediment supply and wind velocity, can be expressed as:

$$H=\frac{S.U}{g}$$

Where H is the dune height, S is the sediment supply, U is the wind velocity, and g is gravitational acceleration [22]. This formula suggests that greater sediment availability combined with higher wind speeds leads to taller dunes, assuming other factors such as vegetation and water level fluctuations remain constant.

7.3.4. Vegetation and Stabilization

Vegetation plays a crucial role in both facilitating and stabilizing the formation of dunes. Plants, especially grasses and shrubs, trap sand through their root systems and reduce the movement of sediments by decreasing the wind velocity near the surface. This process is described by vegetation drag models, where the drag coefficient (k) affects the effective wind velocity ($U_{effective}$) at ground level:

$$U_{effective}=U-k\cdot V$$

Where $U_{effective}$ is the reduced wind velocity, U is the free-stream wind velocity, K is the drag coefficient, and V is the vegetation density [33]. The presence of vegetation reduces the amount of sand transported and helps stabilize dunes, preventing them from migrating or eroding away. Over time, vegetation can become established on dunes, further enhancing their stability and contributing to dune growth [23]. This stabilizing effect is particularly important in freshwater lake environments, where dynamic seasonal fluctuations in water levels and wind conditions may otherwise lead to the destabilization of dunes.

7.3.5. Water Level Fluctuations and Hydrological Influence

Water level fluctuations in freshwater lakes also influence dune formation by altering shoreline

dynamics and sediment deposition. During high water periods, the shoreline is often eroded by wave action, while low water levels expose more of the lakebed, providing additional sediment that may be transported by wind to form dunes [20]. In some cases, the gradual retreat of the shoreline during periods of low water can leave behind areas of sand that accumulate to form new dunes. These fluctuations contribute to the dynamic nature of freshwater lake dunes, as their shape and size can change rapidly in response to seasonal or long-term hydrological variations.

7.3.6. Effects of Climate Change

Climate change presents significant challenges to the sand dune systems at Sandbanks Provincial Park, impacting both their physical and ecological dynamics. Rising temperatures, shifting precipitation patterns, and an increased frequency of extreme weather events are all contributing to these changes.

Increasing temperatures are likely to alter plant communities within the dunes, as species adapted to the current climate may be displaced by those better suited to warmer conditions. This shift in vegetation can affect dune stability, as changes in plant cover influence soil stabilization. Additionally, altered precipitation patterns can impact soil moisture levels, further affecting dune stability. Prolonged drought conditions can decrease vegetation cover, which in turn reduces the dunes' ability to stabilize and increases erosion rates [6].

The frequency and intensity of extreme weather events, such as storms, are also on the rise. These events can lead to accelerated erosion and sediment loss. Heavy rainfall and storm surges have the potential to destabilize dunes and alter their morphology, making them more vulnerable to further erosion [4].

Climate change is also causing fluctuations in Great Lakes water levels, which can affect sediment deposition and dune stability. Higher lake levels can increase erosion along the shoreline, while lower levels may reduce the sediment available for dune formation [5].

Although Sandbanks Provincial Park is situated on a freshwater lake, the impacts of sea-level rise on coastal dynamics and storm patterns may indirectly influence lake-level trends and coastal processes, potentially affecting dune stability and formation [34].

8. Conservation and Management of Coastal Sand dunes

Coastal dunes are vital natural systems that provide significant protection against erosion, storm surges, and flooding. They also support diverse ecosystems and play a critical role in stabilizing coastal landscapes. The conservation and management of these dunes are essential not only to protect infrastructure but also to preserve their ecological functions in the face of growing threats from climate change, human activity, and invasive species.

Sand dunes act as natural barriers, absorbing wave energy and mitigating the impacts of storm surges. By stabilizing the beach environment and controlling wind erosion, they help minimize the transport of sand over roads and buildings. This reduces the need for costly artificial barriers and supports the resilience of coastal infrastructure. Dunes also help preserve freshwater supplies by acting as natural filters, improving water quality through groundwater recharge and preventing saltwater intrusion into aquifers [7].

Effective management of coastal dunes requires a holistic approach that addresses both environmental and human factors. One of the most critical aspects is maintaining the integrity of the dunes through vegetation management and erosion control. Native vegetation plays a crucial role in stabilizing dune systems. Plants such as **Marram grass** (**Ammophila breviligulata**) and **Beach pea** (**Lathyrus japonicus**) help trap sand and prevent further erosion. In areas where dunes are degraded, restoring vegetation can significantly improve dune stability [4]. Additionally, managing human activities, such as restricting foot traffic, is

essential to preventing trampling, which can destabilize dune structures.

The presence of invasive species poses another major threat to the stability and biodiversity of coastal dune systems. Invasive plants like Common Buckthorn (**Rhamnus cathartica**) and Purple Loosestrife (**Lythrum salicaria**) outcompete native vegetation, reducing dune resilience and altering the ecosystem. Invasive animals, such as the European Starling (**Sturnus vulgaris**), further disrupt local wildlife populations. Human activities, including recreational use and development, exacerbate these issues. In Sandbanks Provincial Park, for example, a proposed road construction project was abandoned after environmental assessments highlighted the potential harm to the park's unique sand dunes, rare plant species, and wildlife habitats. Public opposition and concerns about ecosystem degradation played a key role in preserving the area [35].

In managing coastal dunes, it is also important to consider their role in broader coastal defense strategies. Dune restoration projects, such as those carried out in areas along Ontario's lakeshores, aim to enhance the natural protective functions of dunes. These projects may involve engineering techniques, such as the installation of sand fences or geotextiles, to reinforce dune stability [11]. However, it is crucial that these interventions complement, rather than replace, natural processes. Sustainable land-use practices, which account for the dynamic nature of dunes, help reduce the impact of development and ensure the long-term health of these ecosystems [12].

In summary, the conservation and management of coastal dunes require a combination of restoration, monitoring, and careful planning to address both ecological and human challenges. By preserving and enhancing the protective and ecological functions of dunes, it is possible to safeguard coastal environments and infrastructure while maintaining the biodiversity and resilience of these vital systems. Effective management strategies must balance human use with the preservation of these unique and dynamic landscapes.

9. Discussion

This study provides an in-depth evaluation of the sand dune systems at Sandbanks Provincial Park, located along the shores of Lake Ontario, examining their ecological significance, morphological characteristics, formation processes, and vulnerability to climate change. The dunes at Sandbanks serve as critical coastal protection features, absorbing wave energy, mitigating storm surges, and preventing shoreline erosion, thereby safeguarding coastal infrastructure and providing essential habitats for a diverse range of plant and animal species. These findings align with previous research by Smith [6] and White and Green [36], which emphasize the dunes' importance in enhancing biodiversity and providing ecosystem services, such as water filtration and carbon sequestration.

The morphological dynamics of the dunes reflect a complex interplay of historical glacial processes, aeolian action, and vegetation. Sandbanks' dune system, ranging from embryo dunes to more stabilized foredunes and grey dunes, evolves through sediment deposition and wind action. The initial sediment deposits, shaped by past glacial activity, have been further reshaped by natural forces such as wind and water to form the diverse dune types observed today [2, 31]. These findings align with studies by Carter [32] and Hesp [2], which highlight the role of wind and sediment movement in dune development. The slow, continuous process of dune formation, driven primarily by onshore winds, results in the gradual development of complex dune forms that provide natural defenses against erosion and act as buffers against storm surges.

The formation of coastal dunes at Sandbanks is strongly influenced by the dynamic interaction of wind, sediment supply, vegetation, and water level fluctuations. Wind is the primary force driving sediment transport, with stronger winds resulting in

greater sediment accumulation. This is consistent with Bagnold's Law [1], which states that wind velocity is directly proportional to sand movement. Vegetation plays a vital role in stabilizing the dunes by reducing wind speed near the surface, promoting dune growth, and preventing excessive sand movement [33]. The mild wave action in freshwater lakes such as Lake Ontario, compared to marine environments, adds another layer of complexity, as wave action influences shoreline erosion, sediment availability, and the extent of dune development. In periods of high-water levels, shoreline erosion occurs, while lower water levels expose new sediments for wind transport. This interplay between wind and water further shapes the dune landscape.

Comparing the dune sands from freshwater lakes like Lake Ontario and marine environments reveals notable differences in their suitability for construction. Marine dunes, typically composed of well-rounded, uniformly sized quartz sands, may appear ideal for construction due to their consistent grain shape and size [24, 29]. However, the presence of salt in marine sand can negatively affect concrete structures by causing corrosion of reinforcement bars and weakening the overall material [19]. In contrast, freshwater lake dunes like those at Sandbanks consist of more angular, less well-sorted sands, influenced by local geological conditions. While the sand grains in freshwater dunes are less uniform, they are free from the salinity that can pose challenges in construction applications, making them potentially more suitable for certain high-grade construction uses [25, 26]. Nonetheless, extracting sand from these dunes raises environmental concerns, including disruption to local ecosystems and hydrological systems, which need to be carefully managed [28].

An integrated approach to sand dune protection combines conservation and engineering practices to ensure the sustainability and functionality of dune systems. Key conservation actions include continuous monitoring of dune dynamics and biodiversity to evaluate the effectiveness of conservation measures. Increasing public education about the ecological importance of dunes, controlling invasive species, and initiating restoration projects in degraded areas are essential steps to protect native vegetation and enhance dune stability. Additionally, careful management of human access to sensitive dune areas is necessary to prevent habitat destruction [4, 11].

A comprehensive dune management strategy must integrate both conservation and engineering practices to preserve ecological value and improve coastal protection. Such a balanced approach requires collaboration between environmental scientists, engineers, and policymakers to ensure that dune systems are effectively maintained and protected. This approach is particularly critical in light of the challenges posed by climate change, which threatens the stability of dune systems through rising temperatures, shifting precipitation patterns, and increased storm frequency [34]. Although Sandbanks is located along a freshwater lake, the indirect effects of sea-level rise and fluctuating lake levels also influence erosion and sediment transport, highlighting the need for adaptive management strategies [11].

The protective role of dunes in safeguarding coastal infrastructure is significant. Dunes absorb wave energy and stabilize the beach environment, reducing the risk of damage to roads, buildings, and other infrastructure from storm surges and flooding [8]. Recent conservation efforts, such as halting the proposed road construction in Sandbanks Provincial Park, reflect growing recognition of the need to balance development with environmental preservation [35]. These efforts underscore the importance of maintaining dune integrity for both environmental protection and coastal resilience.

Effective conservation and management strategies are crucial for sustaining the health and stability of dune systems. Erosion control

measures, such as planting native vegetation and restricting human access to sensitive areas, are vital for maintaining dune stability. Managing invasive species is also essential to protect native flora and preserve the ecological balance of dune ecosystems [11]. This study's findings align with current best practices in dune conservation and stress the need for ongoing monitoring, adaptive management, and collaboration between researchers, policymakers, and local communities.

Research into the long-term dynamics of dune systems is essential for understanding their response to climate change and human activity. Future studies should focus on integrating recent data with historical observations to better predict dune behavior and inform management strategies. Expanding research to other coastal dune systems, particularly in freshwater lake environments, will provide valuable insights into broader principles and challenges of dune management. Furthermore, advancing modeling techniques and exploring the interactions between ecological and engineering interventions will enhance our ability to manage and protect dune systems effectively.

10. Conclusion

The freshwater lake coastal sand dunes at Sandbanks Provincial Park play a vital role in coastal protection and ecological stability. These dunes act as natural barriers against erosion, absorb wave energy, and provide essential habitats for diverse plant and animal species. Shaped by the interplay of historical glacial activity, wind, and wave action, the dunes evolve through dynamic processes involving sediment transport, vegetation growth, and water level fluctuations. This study highlights the importance of understanding these complex formation and stabilization processes and underscores the need for effective conservation strategies to address environmental threats, such as erosion, invasive species, and the impacts of climate change. The sand from these dunes, free from harmful salt content, may have potential applications in high-grade construction. However, it is not advisable to mine sand from the dunes, as they play a crucial role in protecting local infrastructure and supporting the surrounding ecology. Careful management is essential to avoid disrupting these vital functions.

Climate change presents significant challenges to freshwater lake coastal sand dunes, particularly at Sandbanks, with rising temperatures, altered precipitation patterns, and increased extreme weather events intensifying erosion and destabilizing dune systems. The fluctuating water levels in Lake Ontario further complicate dune stability, making adaptive management strategies essential. This study emphasizes the critical need to preserve the integrity of freshwater lake coastal dunes for both ecological health and coastal resilience, especially as human development pressures increase.

Future research should focus on long-term monitoring of dune dynamics, the effects of invasive species, and the interactions between hydrological and ecological factors to ensure the sustainable management and protection of freshwater coastal dune systems in the face of ongoing environmental change.

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