1 Literature review

1.1 Bar-built estuaries in the ecosystem and the community

Climate change is affecting multiple marine ecosystems globally (**?**). Its been detected that the global oceanic oxygen content has decreased during the last five decades (**?**) and that air temperature is increasing in oceans (**??**). Also, some studies expect that the absolute mean sea level on Chilean coasts rises between 0.35 to 0.74 m in the next 80 years (**?**). The effects of climate change can put at risk the coastal zones, including estuaries and coastal lagoons which are especially abundant ecosystems in flora and fauna.

In addition, there is evidence that there is a decrease in surface wind speeds in Northern Europe (**?**) and an increase in along-shore winds in the Chilean coastal zone (**?**). It is known that changes in surface wind speed affect the number of days that a lake is stratified, which affects the nutrient availability and quality of a waterbody, changing the amount of oxygen present in deep waters (**?**). It is important to study wind effects in estuaries to be able to quantify how wind-speed changes will affect these environments.

In central Chile, there is a decrease in river discharges affecting buoyancy and stratification (**?**), which can be causing a wide range of changes in estuarine and marine ecosystems, including changes in oxygen availability. These changes can impact fish populations and other autotrophic organisms.

The importance of intermittently closed estuaries goes beyond local impacts. These estuaries can accumulate sediment and minerals while the inlet is closed (**?**), and in rainy seasons they open their mouth naturally because of the increase in freshwater inflow (**?**). This process settles sediments to the nearby marshes helping to maintain their elevation according to the sea level, mitigating the consequences of sea level rise (**?**). Usually, the mouth is exposed to artificial openings to avoid flooding the surrounding lands (**?**), which does not allow the sediments to set in the marsh platform (**?**), not allowing them to keep their normal elevation that protects the coastal zone from the sea level.

Climate change is affecting bar-built estuaries' dynamics and water quality.
Increasing river discharge due to more precipitation could lead to increase erosion and the number of suspended particles of sediment in the water. Enhanced sediment concentration could lead to accumulation in the estuary making the inlet close, changing the equilibrium of opened and closed state of the sand bar, which along with the increase of freshwater input could flood the surrounding land (**?**). Consequently, depending on the vegetation present and its oxygen demand, deep-water oxygen may be reduced or suppressed (**??**). Also, the density of the surface waters will be reduced and thus could change the estuary behavior to external factors such as wind stress.

On the other hand, bar-built estuaries are under continuous anthropogenic stress due to their closeness to human settlements (**?**) and their productive importance. Dams constructed upstream for water storage reduce the freshwater that goes to the ocean, causing the retention of suspended sediments. This results in a change in the morphology of the estuary due to not receiving the sediments that used to accumulate in the inlet, leading to premature scour of the sand bar (**?**). Also, to prevent the flood of roads or agricultural lands that settle nearby, the community plan the opening of the inlet artificially, which could result on abrupt changes on the estuary ecosystem **?**.

1.2 How bar-built estuaries are studied in Chile and around the world

There are plenty of methods and instrumental techniques to measure the behavior of estuaries and lakes at a small scale (**?**), methods that can be used with new data and get improved for future works and be more specific for the different types of waterbodies. **?** studied the bar-built estuaries all around the world and their climatic, marine, and fluvial conditions to classify them and quantify the drivers of their distribution in each continent. That can "allow predictions of estuary response to climate change and human impacts to be made and to ultimately assist with integrated coastal management into the future".

? studied a Chilean coastal lagoon in its open and closed state and observed that in its closed state the rainfall influence was not important except for the storms that open the inlet to the sea. He also observed that wind is very important in water level fluctuations in the disconnected phase. He studied the connected phase using a general pattern, spectral, and Fourier analysis.

? observed that in stratified waterbodies, when the vertical exchange is limited, oxygen depletion can occur, causing hypoxia and anoxia, a factor that is related to fish kills in Pescadero (**?**). **?** proposed that tidal influence oxygenated the deeper layers in a saline lagoon in some specific events and observed that the same conditions were present when there was wind-driven upwelling, showing a relation between tidal influence and wind stress in vertical mixing.

? observed the salt intrusion in a bar-built estuary and its differences between closed and open state conditions. The study found the presence of alternating shallow sills and deep pools, which act to trap the salt after intrusion, and suggested that internal seiche motions in the outer estuary initiate the intrusion by lifting saline water in the pycnocline high enough to crest the sills. This salinity intrusion extends to distances of several kilometers from the beach.

Studies carried out in Rodeo Lagoon (**?**), a shallow strongly-stratified lagoon, found that stratification leads to a pronounced suppression of turbulence below the pycnocline and confines nutrients released from the sediment into the lower layer. Bottom water can be confined for several months, compared to the rapidly flushed overlying fresh layer. They observed that in the lagoon wind is the dominant source of mixing because of a lack of other energy inputs and destratification by wind mixing allows for the redistribution of nutrients from the bottom brackish layer.

1.3 Hydrodynamics of a stratified waterbody

In nature, stratified waterbodies can be found not only in estuaries (**?**) but also in lakes (**???**) or coastal lagoons (**?**). Although lakes are usually studied as thermally stratified water systems, they exhibit comparable hydrodynamics to thermal-haline stratified coastal waterbodies. In estuaries, when the tidal connection with the ocean is limited, water circulation is driven by wind and freshwater inflow, resulting in similar dynamics to lakes in a smaller scale.

In stratified lakes or estuaries, it is common to find a two-layered system with the presence of an interface of finite thickness, which is a third middle layer. This middle layer can be observed as a gradient of density or temperature that separates the upper layer from the lower layer. The interface layer thickness is an important parameter that can impact the dynamics of the water column in these types of waterbodies (**?**).

Depending on the strength and duration of wind forcing, the lake or estuary can manifest an upwelling response. The wind's energy is the primary source of energy for the water column's circulation, and it can cause an upwelling response when it is strong enough to overcome the stratification of the water layers. Upwelling occurs when the wind's energy forces the lower layer of water to move upward, bringing nutrients and other materials to the surface that can stimulate primary productivity in the water column (**?**).

? studied the setup and relaxation of spring upwelling in a deep, rotationally influenced lake, Lake Tahoe, using a combination of field observations and numerical modeling to investigate the mechanisms that cause the upwelling of deep water in the lake. They found that the setup of upwelling was caused by the wind-induced mixing of the upper layer of the lake, which resulted in a deeper mixed layer and the buildup of potential energy. The relaxation of upwelling occurred when the wind stopped, and the potential energy was converted into kinetic energy, which led to the downwelling of surface water. These findings provide new insights into the mechanisms that control the dynamics of upwelling in deep lakes and could help inform the management of these ecosystems.

Following a wind forcing event, stratified lakes exhibit layer interactions that may involve upwelling or vertical mixing. This is due to the changes in the water column's stability as the wind energy penetrates the water layers. The Wedderburn number is an useful tool in quantifying the effects of the wind's surface stress on the water column's dynamics in stratified lakes or estuaries. It describes the ratio between the wind's energy and the energy needed to mix the upper layer with the lower layer (**?**).

? discussed that a three-layered fluid has a similar behavior as a two-layered fluid when the upper layer is shallow. This is because the shallow upper layer behaves like a mixed layer, while the middle layer acts as an interface layer separating the mixed layer from the lower layer. When the upper layer accelerates due to a wind forcing in the surface, the mixed layer starts to deepen rapidly, while the upper layer tilts and might upwell (**?**).

The Wedderburn number was design for rectangular basins, but this approach is not too close to reality, where basins can be of multiple and irregular shapes. **?** used a numerical model to demonstrate that the upwelling of deep water in lakes with any geometry can be described using the Wedderburn number as a function of the Richardson number, the buoyancy frequency, and the Rossby number. This Wedderburn number is not a detailed estimate of the interface behavior, therefore provides a scale for the seiching. These results provide a better understanding of the physical processes that drive the upwelling of deep water in lakes and could help improve the management of these ecosystems.

The response of stratified lakes or estuaries to wind forcing events can be complex, involving interactions between the layers of the water column, upwelling responses, and changes in the water column's stability (**?**). Upwelling occurs when the wind's energy forces the lower layer of water to move upward, bringing nutrients and other materials to the surface that can stimulate primary productivity in the water column (**?**). The thickness of the interface layer is an important parameter that can impact the dynamics of the water column in these types of waterbodies (**?**). Factors such as wind strength and duration, water temperature, and the presence of nutrient-rich layers in the water column can all affect the response of stratified lakes or estuaries to wind forcing events (**?**).

1.4 Pescadero estuary studies

Pescadero estuary has literature related to management plans focusing on productivity (**?**) or in preserve the hydrology of the estuary (**?**). But recent studies have been motivated on the fish kills that have been observed in the last years, signaling that when the sandbar closes stratification leads to the creation of an anaerobic environment in bottom waters (**?**). Also, geochemical analysis to sediments showed that the transition from closed to open state leads to poor water conditions within the Pescadero Estuary, with many indicators reaching values that are outside the range of optimal conditions for fish or aquatic life (**?**).

In addition, it has been studied more physical phenomena like the effects of the constriction that generates the mouth in its open state, showing a discontinuous tidal forcing in the estuary (**?**). **?** observed that wave setup and tides set the estuarine water level, while the mouth sandbar limits ocean gravity waves to enter the estuary but permits infragravity motions to pass through the inlet, which induced energetically important high velocities, highlighting the strong dependence of hydrodynamics of small bar-built estuaries on nearshore processes. Also, hydrodynamic processes in Pescadero are comparable to similar estuaries along the western coast of the Americas as well as in Australia, South Africa, and in estuaries in Mediterranean climates on the Atlantic west coast of Europe, as well as in shallow sandy inlets elsewhere.