COMPARATIVE OCEANOGRAPHY OF COASTAL LAGOONS

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Abstract: Coastal lagoons are shallow water bodies, separated from the adjacent ocean by a barrier. Some lagoons have only a narrow entrance channel, which at times may be completely closed off. These are the choked lagoons, which are characterized by dynamic wind forcing, highly variable circulation response, and lack of significant tides. Whereas these lagoons may be fresh water systems in areas of high rainfall and runoff, they sometimes become salt flats in and regions where they can be closed off from the sea for prolonged time periods. On the other end of the spectrum are the leaky lagoons. Such lagoons are either connected by several entrance channels to the adjacent ocean or are separated from it by an incomplete barrier, consisting of a series of sand islands or coral reefs. Leaky lagoons are usually strongly affected by tidal action, have oceanic salinity characteristics, exhibit persistent tidal circulation patterns, and are impacted by wind forcing. Restricted lagoons are intermediary to the choked and leaky extremes. Oceanographic features in ten lagoon systems are compared and classified.

Introduction

Coastal lagoons are among the most common coastal environments, occupy 13 percent of the world’s coastline (Barnes 1980), and have a number of common features summarized by Phleger (1969, 1981). Yet very little systematic, scientific work has been carried out in coastal lagoons in comparison to estuaries. One reason for this might be that coastal lagoons are shallow, less suitable as harbors, and thus often without major population centers. Estuaries, on the other hand, usually have deeper channels, make better harbors, encourage population growth, and are located on historical river-transportation routes. Another probable reason for the lack of scientific studies of lagoons is that the majority of coastal lagoons are located either in lesser developed countries or in sparsely populated areas of developed countries.

Coastal lagoons are found on all continents from the tropics to polar regions but are less common on emergent high-latitude coasts (Nichols and Allen 1981). They are particularly prominent in the low latitudinal zone (Davies 1980). They occupy shallow coastal depressions and are separated from the ocean by a barrier. Like estuaries, they are ephemeral coastal features of recent origin. They were formed during the eustatic rise of sea level between the time of the Wisconsin glaciation 18,000 years ago and the present, and stand the
risk of being completely infilled by sediments or closed off from the sea by littoral drift (Lankford 1976).

Most previous system-level studies of coastal lagoons have focused on biological/ecological characteristics (e.g. Day et al. 1973; Lara-Lara et al. 1980; Nixon and Less 1981; Milan-Núñez et al. 1982; Yáñez-Arancibia and Day 1982; Day and Yáñez-Arancibia 1982; Day et al. 1982; and Farfan and Álvarez-Borrego 1983). Sedimentological regimes in coastal lagoons and processes of lagoon formation have been analyzed by Orme (1975), Lankford (1976) and in an excellent summary paper by Nichols and Allen (1981). The cumulative knowledge of the functioning of these systems has led to management recommendations and some analyses and syntheses (e.g. Lasserre 1979; Lee and Olsen 1985).

Our ability to predict future changes in coastal lagoons depends on an integrated understanding of hydrological and physical-dynamic lagoon processes. A few individual lagoons have been investigated from a hydrographic-hydrodynamic point of view: e.g. Wadden Sea, Denmark, Germany and The Netherlands (Postma and Dijkstra 1982; Zimmerman 1976); Laguna de Terminos, Mexico (Graham et al. 1981); Indian River, U.S.A. (Smith and Kierspe 1981); Laguna Caimanero-Huizache, Mexico (Moore and Slinn 1984); Mississippi Sound, U.S.A. (Eleuterius 1976; Kjerfve 1983); Lake Pontchartrain, U.S.A. (Sakou 1983; Swenson 1981; Chuang and Swenson 1981; Swenson and Chuang 1983; Sikora and Kjerfve 1985); Lagoa dos Patos, Brazil (Herz 1977); Ninigret Pond, U.S.A. (Isaji and Spaulding 1985); and the lagoons of Texas (Collier and Hedgepeth 1950; Copeland et al. 1968; Smith 1977). In other instances, the physical processes in lagoons have been the focus of studies, e.g. wind-induced effects (Beer and Black 1979; Noye and Walsh 1976); and tidal mixing, dispersion, and flushing (Zimmerman 1978, 1981; Dronkers and Zimmerman 1982). Few previous studies have focused on common physical and oceanographic features of coastal lagoons.

The purpose of this paper is to describe and analyze relevant geographical, hydrological, and oceanographic characteristics of coastal lagoons in an attempt to formulate some generalizations. My main hypothesis is that physical lagoon characteristics and variabilities depend primarily on the nature of the channel(s) connecting the lagoon to the adjacent coastal ocean. The channel types vary along a continuum resulting in lagoons which can be classified as choked, restricted, and leaky. At a later time, it may be desirable to parameterize lagoon processes and present the results in a more quantitative fashion than is done here (cf. O'Brien 1969).

**Characteristics of Ten Lagoons**

Initially, I will describe salient physical characteristics of 10 selected lagoon systems (Table 1).

*Laguna Joyuda* (Fig. 1) on the west coast of Puerto Rico, is an example of a choked system (Levine 1981). The lagoon is microsized, measures only 1.4 km², and has a maximum depth of 4 m. The 500-m entrance channel
<table>
<thead>
<tr>
<th>Lagoon</th>
<th>Latitude</th>
<th>Entrance Type</th>
<th>Ocean Entrances</th>
<th>Surface Area (km²)</th>
<th>Mean Depth (m)</th>
<th>Ocean Tide at Entrance</th>
<th>Predominant Salinity Characteristics</th>
<th>R Annual Rainfall (m)</th>
<th>E Annual Evaporation (m)</th>
<th>Q Mean River (m³ s⁻¹)</th>
<th>Offshore Wave Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laguna Joyuda (Puerto Rico)</td>
<td>N18°</td>
<td>Choked</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0.3 - Diurnal</td>
<td>Estuarine</td>
<td>1.73</td>
<td>R &gt; E</td>
<td>0</td>
<td>Low</td>
</tr>
<tr>
<td>Coorong (Australia)</td>
<td>S36°</td>
<td>Choked</td>
<td>1</td>
<td>260</td>
<td>2</td>
<td>0.5 - Mixed</td>
<td>Hypersaline</td>
<td>0.30</td>
<td>E &gt; R</td>
<td>0</td>
<td>High</td>
</tr>
<tr>
<td>Lake St. Lucia (South Africa)</td>
<td>S28°</td>
<td>Choked</td>
<td>1</td>
<td>312</td>
<td>1</td>
<td>1.5 - Semidiurnal</td>
<td>Estuarine</td>
<td>1.00</td>
<td>1.32</td>
<td>20</td>
<td>High</td>
</tr>
<tr>
<td>Gippsland Lakes (Australia)</td>
<td>S38°</td>
<td>Choked</td>
<td>1</td>
<td>340</td>
<td>4</td>
<td>1.0 - Semidiurnal</td>
<td>Estuarine/Brackish</td>
<td>0.67</td>
<td>1.00</td>
<td>100</td>
<td>High</td>
</tr>
<tr>
<td>Lake Songkla/Thale Luang (Thailand)</td>
<td>S7°</td>
<td>Choked</td>
<td>1</td>
<td>1,040</td>
<td>2</td>
<td>0.5 - Semidiurnal</td>
<td>Estuarine/Brackish</td>
<td>2.16</td>
<td>1.84</td>
<td>160</td>
<td>Medium</td>
</tr>
<tr>
<td>Lagoa dos Patos (Brazil)</td>
<td>S31°</td>
<td>Choked</td>
<td>1</td>
<td>10,360</td>
<td>5</td>
<td>0.2 - Diurnal</td>
<td>Fresh/Brackish</td>
<td>1.25</td>
<td>R &gt; E</td>
<td>~4,000</td>
<td>High</td>
</tr>
<tr>
<td>Lake Pontchartrain (USA)</td>
<td>N30°</td>
<td>Restricted</td>
<td>3</td>
<td>1,630</td>
<td>4</td>
<td>0.5 - Diurnal</td>
<td>Brackish</td>
<td>1.52</td>
<td>R &gt; E</td>
<td>188</td>
<td>Low</td>
</tr>
<tr>
<td>Laguna de Términos (Mexico)</td>
<td>N19°</td>
<td>Restricted</td>
<td>2</td>
<td>2,500</td>
<td>4</td>
<td>0.5 - Mixed</td>
<td>Estuarine</td>
<td>1.70</td>
<td>R &gt; E</td>
<td>~600</td>
<td>Medium</td>
</tr>
<tr>
<td>Mississippi Sound (USA)</td>
<td>N30°</td>
<td>Leaky</td>
<td>Multiple</td>
<td>2,130</td>
<td>3</td>
<td>0.5 - Diurnal</td>
<td>Oceanic/Estuarine</td>
<td>1.49</td>
<td>R &gt; E</td>
<td>1,400</td>
<td>Low</td>
</tr>
<tr>
<td>Belize Lagoon/Chetumal Bay (Belize/Mexico)</td>
<td>N17°</td>
<td>Leaky</td>
<td>Multiple</td>
<td>12,700</td>
<td>15</td>
<td>0.2 - Mixed</td>
<td>Oceanic</td>
<td>5.0-0.5</td>
<td>1.80</td>
<td>~400</td>
<td>Medium</td>
</tr>
</tbody>
</table>
winds through dense mangrove vegetation (*Rhizophora mangle*). The channel is typically only 0.4 m in depth and 6 m in width, and is occasionally blocked off by sediments accumulating on the ocean side. The diurnal microtide in the lagoon measures 0.1 m or 30 percent of the tide in the adjacent Mona Passage. Fresh water to the lagoon is derived from ground water and diffuse surface runoff from rainfall over the 6-km² drainage basin. The salinity of the lagoon is largely uniform, varies slowly, and ranges from 8 to 44‰ (Laurence Tilly, pers. comm.).

*The Coorong* (Fig. 2) is a narrow, shore-parallel, choked lagoon system in South Australia, separated from the Southern Ocean by a dune field 50-m high. The average surface area is 260 km². The maximum depth averages 1.8 m in the summer but regularly increases by 1.2 m in the winter (Noye 1973). The lagoon is located in an arid region where evapotranspiration exceeds runoff and rainfall. Accordingly, the lagoon is hypersaline. The northern basin connects to the Southern Ocean via a lake system at the mouth of the Murray River. This is also the main source of occasional fresh water flow into the Coorong, causing salinity variations in the northern basin. The southern basin is entirely hypersaline with an average salinity of 90‰ (Noye 1973). In
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Figure 2. Area map of Coorong, South Australia.

the extreme south, lagoon salinities commonly exceed 200‰ in summer, and little plant and fish life can be sustained (Noye 1973). No water exchange occurs between the northern and southern basins in the summer. The coastal ocean experiences a 0.5-m mixed tide and an extreme wave climate with 4-m (15-s period) waves. These effects do not propagate into the Coorong. On the other hand, the wind stress parallel to the lagoon forces a 0.2-m longitudinal oscillation of water level in each of the two basins with a period of approximately 24 hours (Noye and Walsh 1976).

Lake St. Lucia (Fig. 3), South Africa, is another choked lagoon in a semi-arid region, separated from the Indian Ocean by massive coastal barriers 180 m in height. The water-covered area is 312 km² but increases to 417 km² during the rainy summer period, when the mean water level rises one m (Orme 1975). The average water depth is less than two m, and a long (20 km) entrance channel (the Narrows) connects the lagoon to the high energy wave conditions in the coastal ocean. As a result the strong littoral drift can close off the entrance. The semidiurnal ocean tide measures 1.5 m but is completely filtered out north of the Narrows (Orme 1975). The salinity regime of the lagoon is highly variable on subtidal time scales and also changes seasonally. As an example, the northern end of the lagoon experiences 15‰ salinity during normal rainy seasons but salinities are as high as 50‰ during periods of severe drought (Orme 1975). Sedimentation in Lake St. Lucia is very high and has
been accelerated by human activities. Over the past 5,000 years, the lagoon has experienced a 66 percent reduction in area and a 95 percent reduction in water volume as a result of sediment infilling (Orme 1975).

The Gippsland Lakes (Fig. 4) in southeastern Australia are a series of choked lagoons: Lake King (92 km²), Lake Victoria (110 km²), Lake Wellington (138 km²), and a number of smaller lakes. Five rivers feed the lagoons, draining the 10,000 km² of catchment basin that consists mostly of farmlands (Bird 1978). The three connected lagoons are rather deep with average/maximum depths of 3/5 m for L. King, 4/10 m for L. Victoria, and 3/4 m for L. Wellington. The high coastal wave power formerly resulted in intermittent closure of the entrance to the lakes. However, the present entrance is an artificially cut and maintained navigation channel that remains open at all times. The semidiurnal ocean tide has a range of 1.0 m but is diminished to less than 0.1 m within 10 km of entering the lagoon channel. The combined fresh water inflow averages 100 m³ s⁻¹ with average September high flows of 180 m³ s⁻¹. During times of flood discharge, the water level in the Gippsland Lakes may
rapidly increase by two m and flood adjacent lowlands (Bird 1978). The salinities vary seasonally with spring lows in November and fall highs in May. The typical spring/fall salinities are 20/30% for L. King, 5/20% for L. Victoria, and 0/7% for L. Wellington (Bird 1978). Predominant and resultant westerly winds blow along the length of the lagoon system, causing choppy, 1-m waves on the lakes (Bird 1978).

Lake Songkla/Thale Luang/Thale Noi (Fig. 5) is a 1,040-km² system of choked coastal lagoons in southern Thailand. The mean depth of the lagoon system is 1.2 m, while the channels connecting Lake Songkla to the coastal ocean and to Thale Luang are 5-8 m deep. The surrounding land is low-lying, dominated by extensive rice fields and mangrove vegetation. The 0.5-m semidiurnal tide in the lower Gulf of Thailand is filtered by the entrance channel and measures less than 0.2 m in Lake Songkla. Fresh water input measures 160 m³ s⁻¹ on the average and is derived from rain falling over the 70,000 km² drainage basin. The rainy season is August–December during the SW monsoon and the dry season is January–July during the dry NE monsoon. Lake Songkla, Thale Luang, and Thale Noi have average salinities of 19, 14, and 0.3%, respectively (Asian Institute of Technology 1979; Sojitsuporn 1984). The upper part of the system is largely covered by water hyacinths, Eichornia spp, which impairs the circulation and water exchange.

Lagoa dos Patos (Fig. 6) in southern Brazil is the world's largest choked lagoon. It measures 10,360 km², has a 140,000 km² drainage basin, and connects in its southern extreme to the South Atlantic via a 20-km entrance channel 0.5 to 3 km in width. Porto Alegre, Brazil's fifth largest city and a major port, is situated on the shores of Rio Guiaiba in the innermost region of Lagoa dos Patos, and can be reached by seagoing ships navigated 320 m along the
length of the 5-m (depth) lagoon. Lagoa dos Patos is usually a fresh water system with an estuarine region limited to the entrance channel and extreme southern lagoon. With winds from the north, the entire system is fresh, but with prolonged winds from the south, brackish water (1-5%) may extend inland to the mouth of Rio Guiaba (Delaney 1963). Rio Guiaba supplies 86 percent of
the average total fresh water input of approximately 4,000 m³ s⁻¹. The peak winter fresh water input exceeds 1,500 m³ s⁻¹ annually with extremes exceeding 25,000 m³ s⁻¹ (Herz 1977). The low diurnal tide range in the adjacent South Atlantic vanishes within the confines of the entrance channel. Currents and water level variations are dominated by wind forcing, which causes a highly variable internal circulation (Bonilha 1974). Winds are predominantly from the northeast during all seasons. However, occasional southerly winds are common in June, associated with winter-time frontal passages (Herz 1977). Because of the large area of the lagoon and the low elevation of the surrounding dune-oriented topography, the wind is the major factor controlling circulation and dispersion in Lagoa dos Patos.

Figure 6. Area map of Lagoa dos Patos, Brazil.
Lake Pontchartrain (Fig. 7) is a 1,630-km² saucepan-shaped, restricted lagoon in Louisiana with a depth of 3.7 m. It was formed as a result of two Mississippi River delta-building periods during the last 5,000 years. The lagoon connects to the Gulf of Mexico via three routes: 1) Mississippi River Gulf Outlet (MRGO), a 120-km navigation channel dredged to 11-m depth and completed in 1963; 2) the Rigolets; and 3) Chef Menteur Pass. The 0.5-m diurnal tide range is reduced to 0.1 m within the lagoon. Tidal currents are pronounced at all three entrances. Subtidal water-level changes and currents account for approximately 50 percent of the flow variance (Swenson and Chuang 1983). The tidal prism measures 1.56 × 10⁶ m³ (Swenson and Chuang 1983), and flushing is achieved in 20–105 days (Swenson 1980). Substantial subtidal currents and water-level changes result from wind forcing and far-field Gulf effects (Chuang and Swenson 1981). On the average, Lake Pontchartrain receives 188 m³ s⁻¹ of fresh water from numerous streams plus a fraction of the 305 m³ s⁻¹ Pearl River discharge, which debouches into Lake Borgne near the entrance to the Rigolets. Lake Pontchartrain is a well-mixed brackish lagoon with a mean salinity of 5.4‰ near the Rigolets and 1.2‰ in the channel between Lakes Pontchartrain and Maurepas but with annual salinity variations of 8‰ (Sikora and Kjerfve 1985). As a result of the construction of MRGO, the mean salinity increased by 1 to 2‰ (Sikora and Kjerfve 1985). To protect New Orleans from Mississippi River floods, the Bonnet Carré Floodway was completed in 1931. It has been operated seven times (from 13 to 75 days each time) with discharges varying from 1,950 to 6,343 m³ s⁻¹ (Sikora and Kjerfve 1985). Lake Pontchartrain became a fresh water system within two days of the opening of the Bonnet
Carré release structure and returned to average conditions within two months of the end of floodwater release (Sikora and Kjerfve 1985).

*Laguna de Términos* (Fig. 8) with a 2,500-km² surface area, including fluvial lagoon systems and marshes, is the largest lagoon in Mexico. It is an example of a restricted system, connecting to the Gulf of Mexico via two main inlets, El Carmen and Puerto Real, and several smaller inlets. The lagoon is 4 m deep and surrounded by low-lying mangrove swamps. The tide is mixed with a 0.3–0.7 m range and corresponding oscillatory tidal currents throughout the lagoon. The Palizada, a distributary of the Usumacinta river system, discharges an average 500 m³ s⁻¹ of freshwater into *Laguna de Términos*. During September floods, the Palizada discharge may exceed 3,000 m³ s⁻¹ and is then responsible for the input of vast quantities of terrigenous silts and clays to the southwestern end of the lagoon. Two smaller rivers, Chumpan and Candelaria, add an average 100 m³ s⁻¹ to the freshwater input. The typical salinity is 27‰, but it varies seasonally both with distance from the Palizada and with depth (Botello 1978). At the Gulf entrances, the salinity is typically 32–35‰ (Botello 1978; Yáñez-Arancibia et al. 1983) except during floods when salinity in El Carmen Inlet may be depressed to 20‰ or less. Most of the rains occur from June to October. During the dry season (February to June), trade winds from the southeast and east predominate and cause net water movement entering through Puerto Real and exiting through El Carmen inlet. This is the common circulation pattern which exists into the fall. During “norte”
wind events from October to February, however, the circulation pattern may reverse directions.

Mississippi Sound (Fig. 9) measures 2,130 km$^2$ and is a leaky lagoon with a 3-m mean low-water depth. It extends 130 km along the Alabama and Mississippi coastlines and is separated from the Gulf of Mexico by a series of low, sandy barrier islands. It connects to Lake Borgne in the west and Mobile Bay in the east. Half a dozen or more wide tidal passes readily permit water exchange between the lagoon and the Gulf. Because of the leaky nature of the barrier, waves from the Gulf propagate unimpeded into Mississippi Sound. During passages of hurricanes, storm waves often strike the low-lying, densely-populated inner shoreline. The tide is diurnal and has a range of 0.5 m. Although tidal currents account for more than 50 percent of the flow variance, the lagoon responds rapidly to wind forcing (Kjerfve 1983). This is evidenced by sub-tidal sea level variations up to one m and persistent net currents in the tidal passes. Circulation is usually developed in the passes where currents may reach 1.0 m s$^{-1}$. The circulation within the lagoon is weak and variable, and the system is coherent and vertically well-mixed (Kjerfve 1983). Two major rivers, Pascagoula and Pearl, discharge into the lagoon an average 417 and 362 m$^3$ s$^{-1}$, respectively. During peak floods, each river may discharge more than 3,000 m$^3$ s$^{-1}$. In addition, a fraction of the discharges from the Mobile and Mississippi River systems enter Mississippi Sound. As a result, the salinity regime is variable and characterized by multiple, sharp fronts. Most commonly, the salinity varies from 20 to 35‰ (Kjerfve 1983; Eleuterius 1976).

The Belize Lagoon/Chetumal Bay (Fig. 10) system is a 12,700 km$^2$ leaky lagoon along the east coast of the Yucatan peninsula. The region is a shallow, reef-rimmed carbonate platform (James and Ginsburg 1979). Numerous tidal passes intersect sections of the shore-parallel barrier reef, the most extensive coral reef in the Americas, and connect the lagoon to the adjacent Caribbean Sea. Sandy cays and mangrove-covered islands are scattered throughout the lagoon, especially in the middle section. This tropical lagoon is effectively divided at the Belize River delta into two separate lagoons. The northern system is uniformly 4 m in depth, largely land-bound, and surrounded
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by mangroves. The southern system varies in depth from an average 10 m over most of the area to 65 m in the south. The main connection to the Caribbean Sea is an open entrance 25 km wide from which a trough 35 m deep stretches 45 km northward into the lagoon. Sediment profiles across the lagoon indicate a gradient from fine, organic-rich, terrigenous silts and clays at the coast to calcareous silts and clays adjacent to the barrier reef (Miller and Macintyre 1977). The annual rainfall measures only 0.5 m in the semi-arid north to five m annually in the humid tropical southern extreme. Salinity exceeds 30% over most of the lagoon except for a band of low-salinity coastal water along the mainland coast in the south, where high-discharge rivers enter the lagoon (Purdy 1974). Belize Lagoon, in particular, is influenced by northeasterly trade winds, experiences occasional hurricanes (Kjerfve and Dinnel 1983), and is susceptible to high, choppy waves. The tide is mixed diurnal with a 0.2-m range and progresses the length of the lagoon system from south to north in 2.1 hours (Kjerfve 1981).

Discussion

Coastal lagoons can conveniently be classified into choked, restricted, and leaky systems. This appears to be a useful division, as each type exhibits a number of functional similarities. The nature of the channel(s) connecting the lagoon to the adjacent ocean controls, more than any other parameter, how the system functions. Choked lagoons are characterized by a single entrance channel and a small ratio of entrance channel cross-sectional area to surface area of the lagoon. They are dominated by the hydrologic/riverine cycles; have long residence times; are wind forced; and experience limited short-term marine variability. They are most common along coastlines with medium to high wave energy. Leaky lagoons, on the other hand, are characterized by multiple entrance channels and a relatively large ratio of entrance-channel cross-sectional area to surface area of the lagoon. They are dominated by marine influence, near-oceanic salinities, strong tidal variability, and occasional significant wave energy. Restricted lagoons represent the middle of the spectrum of lagoons between the choked and leaky extremes.

Choked lagoons are most common on coasts with high wave energy and low tidal range. Strong coastal wave action in combination with available sediment produces littoral drift, which builds the barrier that separates lagoon and ocean, e.g. Lagoa dos Patos. If the littoral drift is substantial, the lagoon may temporarily become closed off from the ocean, e.g. Gippsland Lakes and Lake St. Lucia. On the west coast of Mexico, the closing and opening of lagoon entrance channels is a seasonal cycle (Moore and Stilin 1984). These choked lagoons are closed off from the sea during the dry season. As they are filled by runoff during the rainy season, the channel reopens.

In arid climates, e.g. South and Western Australia, closed-off lagoons may turn into salt flats for periods up to ten years (Patrick Hesp, pers. comm.). Occasional heavy rains and flood runoff can refill the lagoon basin, percolate through the barricaded entrance, and eventually weaken and break through
Figure 10. Area map of the Belize Barrier Reef Lagoon, Belize, and the adjacent Chetumal Bay, Mexico, along the Caribbean shores of the Yucatan peninsula.
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the barrier. As fresh water input dwindles, salt water will intrude and evaporation will greatly exceed combined runoff and rainfall. As the channel is blocked off by littoral drift, the lagoon will again turn into a salt flat.

Tidal influence in choked lagoons is usually confined to the entrance channel. As a consequence, variability of current and water level is largely related to wind-forcing over a spectrum of frequencies from minutes to weeks. Seiching and set-up/set-down cycles are particularly intense in response to frontal passages (Copeland et al. 1968; Kjerfve 1983; Schwing et al. 1983). In general, systematic wind-driven circulation patterns are poorly developed and highly variable. Many choked lagoons experience seasonal water level changes with a range exceeding one m in response to onset of the rainy season, e.g. the Coorong and Lake St. Lucia. Similarly, the salinity distribution lacks tidal variability but responds rather to changes in fresh water input on scales from days to months, e.g. Laguna Joyuda and the Lake Songkla system. The climate and hydrological cycles control the magnitude and frequency of the low-frequency salinity variability. A system can change seasonally over the entire range from fresh water lagoon to hypersaline lagoon, to salt flat in extreme cases. Choked coastal lagoons are typically not susceptible to oceanic far-field forcing (Wang and Elliott 1978). Flushing times are usually on the order of months.

Restricted lagoons are usually located on low/medium wave energy coasts with a low tidal range. They are usually connected to the ocean by two or more channels which typically remain open at all times. Tidal water level and current variability are readily transmitted into the lagoon without excessive filtering, e.g. Laguna de Terminos. As a result, restricted lagoons exhibit well-defined tidal circulation, which is modified by wind forcing and fresh water runoff. Low frequency sea level changes in restricted lagoons are less a function of runoff than far-field oceanic forcing, transmitted into the lagoon, e.g. Lake Pontchartrain (Chuang and Swenson 1981). Restricted lagoons are less likely to undergo dramatic fluctuations in salinity as compared to choked lagoons. For the most part, restricted lagoons have rather homogeneous salinity, e.g. Laguna de Terminos (Botello 1978), ranging anywhere from 1–35‰, depending on the fresh water input. They are usually well mixed vertically. Fresh to brackish water is found near the river mouths. During flood discharge the entire restricted lagoon may turn fresh or brackish. Because of the small tidal range and the occurrence of near uniform salinity over large areas, semidiurnal/diurnal tidal salinity variations are minimal except in the entrance channels and tidal passes, e.g. Lake Pontchartrain (Sikora and Kjerfve 1985).

Leaky lagoons are connected to the ocean by wide tidal passes (rather than entrance channels) that transmit oceanic effects into the lagoon with a minimum of resistance. The separating barrier can be either a series of sand islands e.g. Mississippi Sound, or sections of a barrier reef. A reef can be either of coral origin as in the case of the Belize Lagoon/Chetumal Bay system and the Great Barrier Reef in Australia or of sandstone origin as in the case of the reefs along the coasts of northeastern Brazil (Mabesoone 1964) or western Australia (Allison and Grassia 1979). Leaky lagoons are located along coasts
with variable tidal and wave characteristics. However, tidal currents must be sufficiently energetic to keep wave-generated littoral drift from closing off the passes. In areas of high tidal range, leaky lagoons exist despite high wave energy conditions, e.g. Great Barrier Reef and Wadden Sea. On coasts with low tidal range, leaky lagoons may still exist as long as wave energy conditions are also low, e.g. Mississippi Sound.

Leaky lagoons are usually characterized by near-oceanic salinities. However, in regions of a lagoon where river runoff is significant in comparison to local tidal exchange, estuarine salinities may persist. The occurrence of a complex pattern of sharp salinity and turbidity fronts is then common, e.g. in Mississippi Sound (Kjerfve 1983) and Belize Lagoon/Chetumal Bay. Tidal circulation patterns in leaky lagoons are usually well-defined but are sometimes modified dramatically by wind forcing. Frontal passages may cause lagoon-wide water level seiching and high wave energy conditions. Leaky lagoons are readily flushed. Most large leaky lagoons are oceanic, rather than estuarine in regard to salinity.

**Final Comments**

I propose that coastal lagoons (rather than bar-built estuaries) be considered as one of the three major classes of estuaries in addition to drowned river valleys and fjords. This requires an extension of the standard, narrow definition of estuaries (Cameron and Pritchard 1963) to include systems with salinity ranging from fresh to hypersaline. An estuary is then a semi-enclosed body of water, at least intermittently in open connection to the coastal ocean (c.f. Kjerfve, in press).

Coastal lagoons can conveniently be subdivided into choked, restricted, and leaky systems. The type of channel connecting the lagoon to the ocean defines the salient oceanographic characteristics of the system. Dynamic processes due to tides, wind, and density currents are often of equal magnitude, making it difficult to separate these effects.

Future scientific investigations of lagoon processes could benefit from techniques employed in the study of drowned river valley estuaries. Coastal lagoons lend themselves particularly well to numerical circulation/dispersion modeling. Because of weak vertical stratification, two-dimensional tidal models usually work well. In addition to conventional study approaches with moored instruments and hydrographic survey vessels, remote sensing techniques (c.f. Girloff-Emden 1976) are likely to yield useful results in coastal lagoons because of the large surface areas, lack of significant vertical stratification, and sharp density and turbidity fronts. For example, the satellite-sensed turbidity distribution in a coastal lagoon can provide a good synoptic clue to the circulation (c.f. Herz 1977).

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